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Port Fuel Injection (PFI) Strategies for Lean Burn in Small Capacity Spark Ignition Engines

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ABSTRACT

Port Fuel Injection (PFI) is most dominant technology since 1980 and it will continue to contribute for SI engine in next upcoming years. In PFI system fuel and air are combined in intake manifold and flows through intake system to the combustion chamber. It has brought a higher degree of control in air to fuel ratio, fuel delivery compared to carburetor which could be adjusted according to combustion stability, emissions and engine specific power. In short PFI is simple, robust and low energy requirement system which is being used in modern class A and B vehicles to meet Euro 5 emission levels. Different kinds of PFI strategies have been considered at low engine load and speed to study its effect with respect to engine flexibility and emissions. In such kind of strategies injection can be implemented during open valve injection (OVI) which is also called as "semi-direct" injection or closed valve position (CVI). Different strategies will have different kinds of effect on fuel evaporation which will help to reduce unburned HC emissions. Till now close valve injection strategy is being used in SI engine but it has some limitations. In this paper dual injectors strategies have been evaluated, also concept of stratification which is produced during OVI is considered to extend lean combustion limit. Strategies have been presented to get effect equivalent to Gasoline Direct Injection (GDI) without use of high pressure direct injection and help to get rid of expensive technology of GDI.

Keywords— PFI Strategies, Injection Timing, Lean Combustion

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I. Introduction

As emission norms are getting more stringent, it is necessary to develop cost effective solutions to meet upcoming Euro norms.GDI is said to be most promising technology to meet upcoming norms but in cost wise manner it fails in case of smaller A and B segment vehicles. In such cases PFI engines are still suited for emerging market; these kinds of engines are fuel efficient and exhibit low levels of emissions. Further research has been done to get lean combustion to improve fuel consumption. With improvement in fuel consumption other benefits are also there which includes reduction in knock tendency at high load, low temperature of combustion which indirectly reduces thermal NOx formation and improvement in thermal efficiency. But some things are need to be taken care to avoid misfire, poor combustion stability which could degrade the engine performance .The combustion stability can be poor at idle and low load operation because of heavy throttling, exhaust gas residual which can reach up to only 30% and velocity of charge is minimum. These things will affect flame burning speed. One way to get control of stratification is by phasing of opening valve periods, fuel injection timing and by improving in strength of air motion.

Port Fuel Injection

Fuel injection concept has been introduced in internal combustion engine from 1980 onwards. Main difference between fuel injection and carburettor is that atomization of fuel under high pressure level in fuel injection while carburettor depends on suction which is created because of accelerated intake air. In port fuel injection fuel-air mixture gets prepared in intake system and entered into combustion chamber. Fuel injector injects required amount of fuel with precision into intake port according to different conditions.

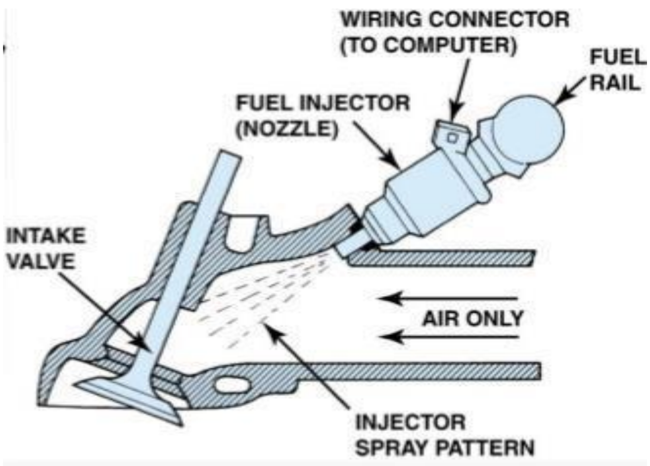

Fig.1 Schematic Diagram of Port Fuel Injection

PFI systems are not exposed to high pressure and heat of combustion chamber and injection pressure varies from 3 bar to 5bar which is far lower than GDI system. Fuel injector injects fuel when valves are in closed position and fuel will remain over there till valve gets open which helps in evaporation of fuel. But this condition won't be better when engine speed gets increased which could lead into increase in HC emissions. There are several types of PFI system like single point injection, sequential injection, multi point injection and split type injection. Single point injector injects fuel below 5 bar pressure in which evaporation and air mixing occurs before cylinder chamber. If there is more distance between injector and intake valve then there are chances of variation of AFR are likely to occur. In case MPI one injector will be used per cylinder and injectors are located very nearly to valve to improve transient response. Engine load gets controlled by throttle to vary flow rate of air into intake system. ECU calculates injection duration (1.8ms to 20 ms) and amount of fuel to be injected. If fuel gets sprayed over surfaces other than back of valve then there is increase in wall wetting and fuel film pools [3]. This issue will become critical at cold start conditions and it can be resolved with the help of different kinds of PFI strategies. The objective of this paper is to study PFI strategies for improvement of engine performance and reduction in fuel consumption which could give low cost based solution. Single and double fuel injection strategies are being considered in CVI and OVI condition. Variation in AFR causes cyclic to cyclic variation in flame development that affects maximum pressure, burn rate, gross indicated mean effective pressure and maximum rate of pressure rise. To avoid these conditions it is required to ensure that coefficient of variation (COV) is less than 10%. Based on different timing, study has been conducted with different cases and it shows that each case has different kind of benefits and it will vary according to engine conditions. In first case of study conventional strategy that is close valve injection is used. It shows considerable reduction of ubHC emission at cold start and low load [4, 5]. The main reason behind reduction of HC is evaporation and it depends upon for how long fuel remains in contact with inlet valve that is fuel residence time, but it will decrease with respect to engine speed. In CVI there is less interaction between air flow and fuel spry interaction since, there is no mean flow velocity components. But having decaying motion because of which small droplets tend to decelerate and large droplets maintain its trajectories till it gets hit by valve or walls. Whenever droplets hit the wall or valves, there will be formation of liquid fuel film or rebounding and change in trajectory of droplets. This will subjected to atomization because of shear forces between gas and liquid phase. It is also required to consider effect of backflow during heavy throttle condition or for valve overlap having large periods. Homogeneous mixing is having benefits in PFI engines and also not suitable to have liquid fuel present in combustion chamber [6].Thus, CVI includes some benefits like more time for fuel to get evaporation, lower cold start emissions despite having some disadvantages like low volumetric efficiency, port wall wetting etc. Researcher reported four ways by which liquid droplet can be transported into combustion chamber in PFI.

Flow atomization

Intake air transport at high speed Squeezing of fuel film

Contribution of injection

The first case will cause during close valve injection that is reverse flow at intake when there will be enough shear force between air flow and liquid fuel which will cause strong atomization. The second case will takes place when fuel is being transported into the cylinder. Fuel is dragged close to valve and it will get atomised. Third case will occur at end of intake process as valve gets closed and if any fuel droplet is present in valve area then it will get squeeze into combustion chamber or back into port. The last case will happen with OVI because of strong interaction between fuels spray and air flow which could result in more sensitive injection characteristics [7]. For OVI, there is change in air flow rate with speed and shows change in fuel trajectory at different speed. If large droplets are present then it will hit the wall opposite to intake valve or surface around valve of exhaust due to which during cold start and high load, OVI may cause plug wetting. In case of heavy throttle condition or closing of valve at early stage can cause to experience reverse flow within valve overlap period in both cases. After intake valve gets open the reverse flow will tend to drag smaller droplet in opposite direction to cylinder which will lead to improvement in fuel evaporation. Benefits of OVI over CVI includes faster response in transient condition , In-cylinder charge cooling effect, stratification at certain level and reduction in port wall wetting [8,9,10].

II. PFI STRATEGIES

Different kinds of PFI strategies are studied which includes independent fuel injectors injecting separately into intake ports. It includes variation of different parameters like number of injectors, side injection and phasing method which is used to control AFR within cylinder. Different parameters like residual gas fraction, gas properties which are not possible to get through experiment can be determined through simulation approach like RICARDO WAVE model. In this case three different cases have been considered based on speed and IMEP which includes 1bar and 1000rpm (CASE-1), 1.5 bar and 1500 rpm (CASE-2) and last one include 1.8bar and 1800 rpm (CASE-3).

CASE	CASE -1	CASE-2	CASE-3
Speed (rpm)	1000	1500	1800
Load GIMP (bar)	1.0	1.5	1.8
AFR (range)	13-18	13-20	14-23
Fuel Pressure (bar)	3.5	3.5	3.5

Table.1 Test point conditions

Based on this different configuration dual injection strategies are studied. Different strategies includes are as per following cases:

I. CVI with equal quantity of fuel injected simultaneously (at port A and port B).
II. OVI and CVI with phased injection (twin port)
III. OVI and CVI with equal quantity of fuel injected (multiple fuel injection) in one port only.
IV. CVI with single side injection.
V. OVI with single side injection.

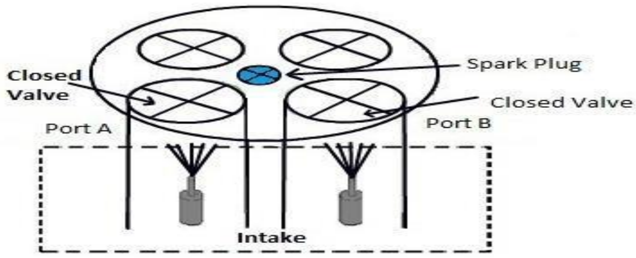

Fig.2 CVI with equal quantity of fuel injected simultaneously (at port A and port B)

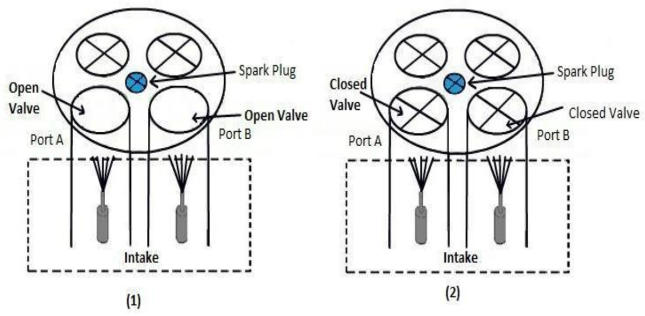

Fig.3 OVI and CVI with phased injection (twin port)

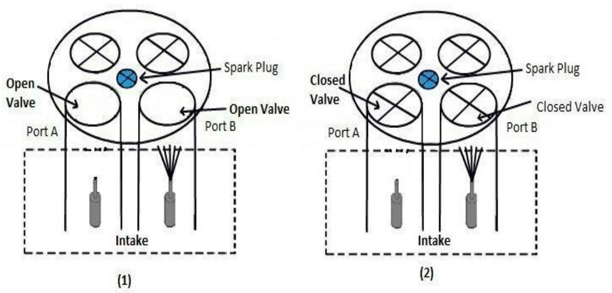

Fig.4 OVI and CVI with equal quantity of fuel injected (multiple fuel injection) in one port only

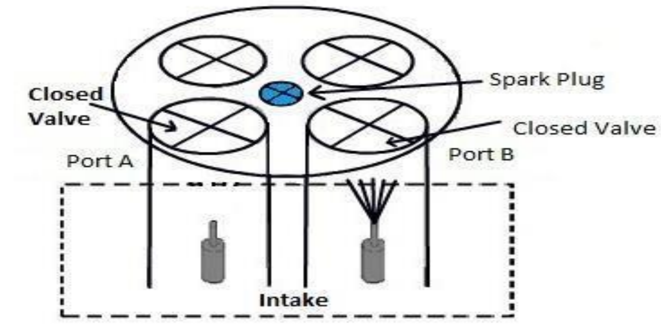

Fig. 5 CVI with single side injection (Port B)

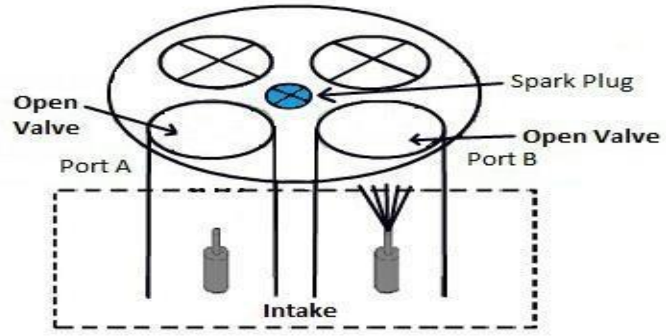

Fig.6 OVI with single side injection (Port B)

To obtain better combustion stability it is necessary that COV should be less than 10% so as to reduce cyclic to cyclic variation. OVI with dual injection strategy has highest dwell time period which could be implemented at high speed. By using heat release model it is possible to get angle of combustion burn for different kind of strategies which will be used to get heat release rate based on ratio of specific heat. Initially CVI timing is set to be at 90 crank angle degrees before TDC and in case of OVI it was set close to EVC. During phased injection timing was set such as one injector will inject during CVI and another will inject at OVI. Multiple injections are based upon injection of fuel at twice in same cycle in one port which includes first OVI and then CVI. In all cases AFR has been varied with respect to speed and load. It is necessary to maintain that half amount of fuel will be split at each port. Results have shown better combustion stability even at lean mode with dual injection strategy. Case-2 and Case-3 with split type and phase injection strategy shows excellent combustion stability. For Case-2 AFR was extended from 19:1 to 20:1 and in case of Case-3 it was extended from 21:1 to 22:1.Each time phased injection has showed better results irrespective of injection timing. In case of Case-2, worst combustion stability was found for single injection strategy. Port B with respect to Case-2 shows good level of achievement with COV (GIMP) of 10% for air fuel ratio of 21:1.The one thing should be noted in case Case-2 and Case-3 that half of the fuel should be delivered at CVI and another half should be delivered at OVI time period. Case-1 shows distinct variation in results with implementation of multiple injections timing for air-fuel ratio up to 17:1 approximately.

III. PERFORMANCE AND COMBUSTION CHARACTERISTICS

In this paper stability in combustion was a main criterion which has been achieved through different configurations and it was found that COV is less than 10%. Heat release was determined from trace of pressure. Relation between stability and combustion duration is determined at different AFR.

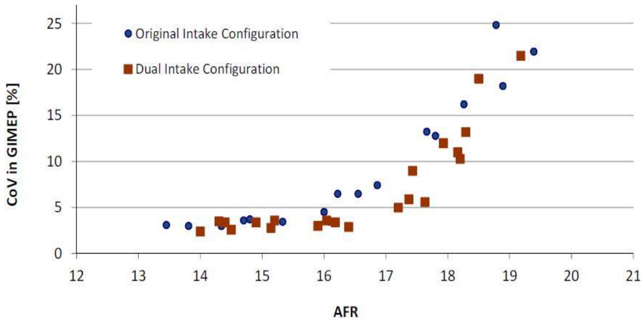

Fig. 7 AFR for different configuration at 1.5 bar GIMP and 1500rpm

Dual intake configuration shows good achievement in terms of combustion stability. AFR of 16.2:1 was recorded as last point for COV in terms of GIMP (below 5%) with original configuration. Up to extension of 5% level of COV to 16.5:1 was found with dual intake configuration. Same kind of situation can be seen for 17:1 AFR as stable combustion limit (10%) for original configuration and 17.5:1 for dual intake configuration. With COV of GIMP between 2 and 3%, both configurations show same behaviour for AFR up to 16:1.

<u>(CASE -1)</u>

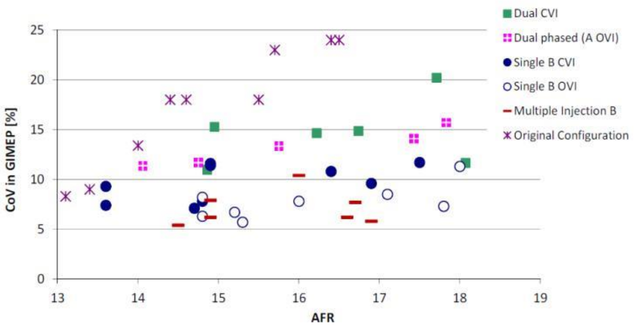

Fig.8 Response of mixture at 1.0 bar and 1000 rpm

This condition with 1.0 bar and 1000 rpm is idling condition where engine was throttled fully. It was found that performance of combustion was poor under these conditions. The possible reasons beyond poor combustion were high residual gas because of previous cycle and transfer of heat to chamber surface due to long availability of time. In case of original configuration there was good combustion stability only at rich mixture (AFR lower than 14:1). In case of OVI in port B it can be seen that COV is under 10% for AFR from 14:1 to 18:1.With help of multiple injection, it is possible to extend lean value up to the AFR of 17:1.

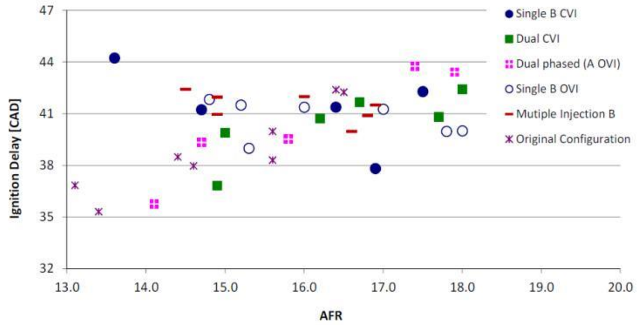

Fig.9 Ignition to 10% of mfb (ignition delay) at 1.0 bar and 1000 rpm

Single port injection in case of side B shows non linear response with respect to variation of AFR. It was founded that ignition delay occurs to be fluctuate between 39 and 42 CAD with change in AFR. No correlation is to be occurred between ignition to 10% mfb and COV. But results are said to be change on the basis of MBT timings.

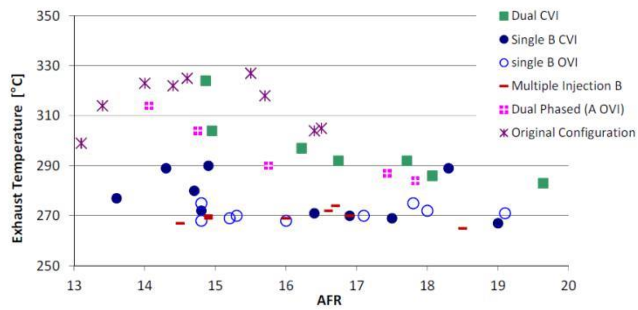

Fig.10 Variation in exhaust temperature at 1.0 bar and 1000 rpm

At this condition temperatures were found to be 100°c lower than Case-2 condition. Lowest temperature was found at single injection of B side which suggest that possibility of shortest duration. In this case, it was found that exhaust temperature was higher for dual injection strategies which was result of longer burn duration occurring while expansion stroke. This will result in heat loss with decrease in efficiency.

<u>(Case-2)</u>

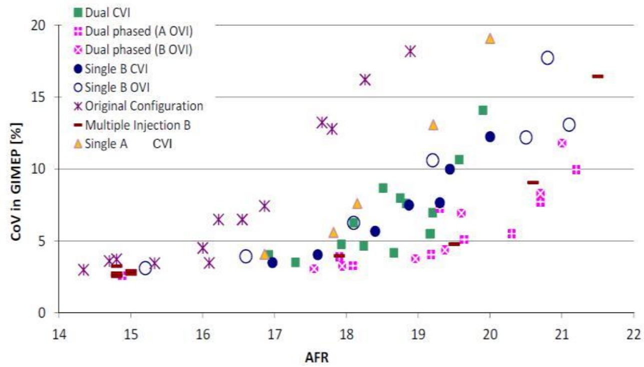

Fig.11 Response of mixture at 1.5 bar and 1500 rpm

Poorest combustion stability can be seen in case of single injection on side A with COV of 13% with AFR of 19.2:1 but still there is improvement as compared to original case. Dual injection with phase strategy shows good combustion stability with COV below 5% up to AFR of 19:1 and below 10% for AFR up to 21:1.This means there is 4%

improvement in AFR compared to original configuration which has AFR of 17:1.It was estimated that single injection with tumble motion will help in fuel stratification but it was reported that it won't help in combustion stability. It was noted that there is improvement in COV (up to 9%) for AFR of 20.6:1 for port B with multiple injection strategy. Finally it was identified that three different configurations shows improvement in combustion stability.

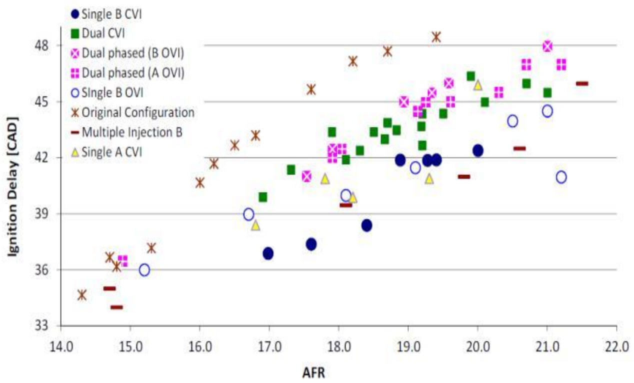

Fig.12 Ignition to 10% of mfb (ignition delay) at 1.5 bar and 1500 rpm

Single injection strategy for port B shows short ignition delay especially at CVI. It was 3 CAD shorter compared to the dual injection strategy for less than 19:1 AFR. Port B with multi injections also shows short ignition delay which concludes that small degree in stratification could lead into unequal flame propagation. Hence it was estimated that shortest ignition delay was because of fuel rich clouds near area of spark plug.

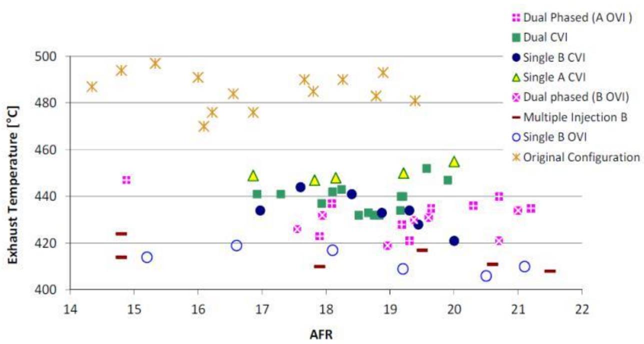

Fig.13 Variation in exhaust temperature at 1.5 bar and 1500 rpm

It was founded that there is reduction of 30̊c to 40̊c of exhaust gas temperature for dual injection strategy. It is because of longer duration of burning period while having poor mixing and divergence from MBT. In case of port B, lowest exhaust temperature was noted for OVI. The reason behind low temperature could be increase in evaporation in cylinder which leads to lowest compression temperature.

(Case-3)

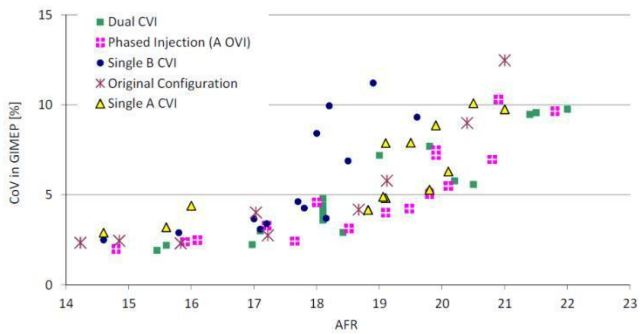

Fig.14 Response of mixture at 1.8 bar and 1800 rpm

In this final set of condition multiple injections was not considered. It was noted that original MBT timing was slightly different than that of MBT obtained for several test point. There is improvement in combustion stability as compared to Case-1 and Case-2.Dual injection configurations are showing COV less than 5% up to AFR 19:1.It was because of high load and speed which leads to improvement in mixing and increment in charge density. It was found that best combustion stability can be achieved in case of dual injection strategy with CVI with extension of AFR from 21:1 to 22:1.This fact was because of overall air-fuel homogenisation.

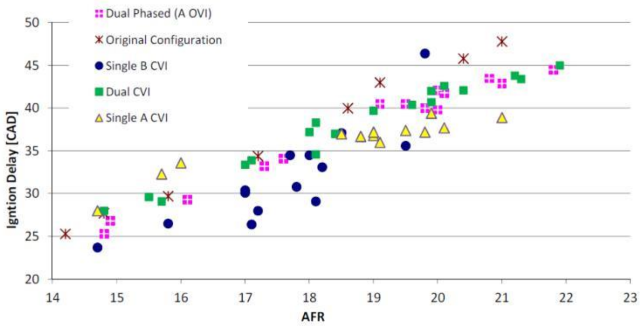

Fig.15 Ignition to 10% of mfb (ignition delay) at 1.8 bar and 1800 rpm

In this case, each injection strategy has shown almost similar behaviour with lean AFR which has lead to the increased in ignition delay. Port B shows shortest ignition delay with AFR up to 17:1 while port A shows long ignition delay for same case.COV has been found above 10 % in case of port B with single injection with AFR of 18:1. In other side port A with single injection shows short ignition delay with AFR greater than 18:1 while stable combustion is there up to AFR of 20:1.

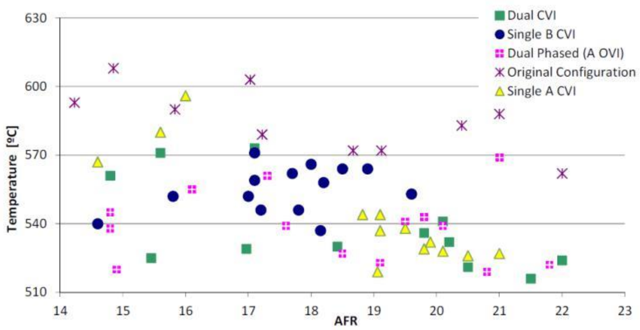

Fig.16 Variation in exhaust temperature at 1.8 bar and 1800 rpm

Again dual strategy has proved to be effective in case of maintaining low exhaust gas temperature.

Hydrocarbon Emissions

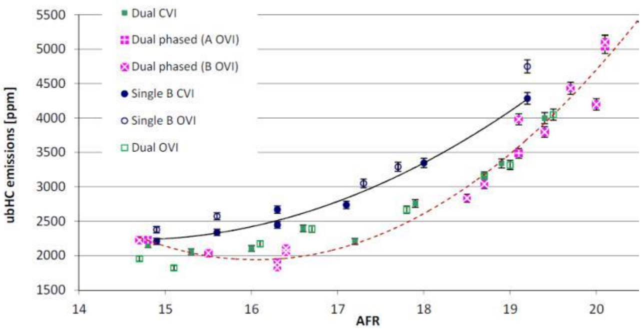

Fig.17 Variation in ubHC with respect to AFR for different cases

It can be seen that there is high level of ubHC in single sided injection compared to dual injection at lean AFR and it was found that it does not depends upon CVI and OVI injection timings. However it should be noted that most stable case that is single side injection in port B with close valve injection will result in more ubHC emissions irrespective of AFR range. In case of CVI, fresh charge may get displaced due to evaporation of fuel in intake port. In case of OVI, there is induced charge cooling effect which could result in higher peak with end in temperature of combustion and low ubHC emissions. It was found to be reduction in evaporation and thicker wall films because of low wall temperature in case of CVI.

IV. CONCLUSIONS

1) It is possible to get stratification in PFI engine by aid of different kind of PFI strategies. Different kinds of difficulties has been identified like poor combustion stability (particularly at idle and low engine load) and it was found that lean combustion mode with stratification is helpful to overcome this kind of situation.
2) In case of idling condition, original configuration has shown good characteristics for rich AFR mixture (14:1). It is possible to extend lean limit up to 17:1 by implementation of dual injection during idling state.
3) At low load and low speed, single sided injection is found to be best solution for improving combustion stability. Lean limit was extended from 17:1 to 21:1 by implementation of phase split injection.
4) Stability has been found for multiple injections in single port only. These kinds of strategies consist of common point that half of the fuel gets delivered during OVI and remaining half will get delivered at CVI. Emission point of view, dual injection is most suitable strategy.
5) It is found that by using combination PFI strategies, it is possible to get stable combustion even at ultra lean mixture at low speed and low load condition. It is possible to get improvement in fuel efficiency in typical operating range of engine which will be helpful in city driving condition. Also Nox and ubHC can be controlled with the help of these strategies to meet upcoming future EURO norms.

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