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Dossier

Diesel Engines and Fuels: a Wide Range of Evolutions to Come
Motorisation et carburants Diesel : un large spectre d'évolutions à venir

Variable Valve Actuation Systems for Homogeneous Diesel Combustion: How Interesting are They?

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Résumé — Distribution variable et combustion Diesel homogène : quel intérêt ? — Avec un bon rendement thermique couplé à des émissions de dioxyde de carbone (CO_2) faibles, les moteurs Diesel sont aujourd'hui très bien placés pour être des possibles leaders dans le domaine des transports de demain. Toutefois, l'évolution attendue des normes nécessite que leurs émissions d'oxydes d'azote (NOx) et de particules soient réduites. Une alternative intéressante à un post-traitement des NOx est liée à l'utilisation de nouveaux procédés de combustion afin de réduire les émissions à la source : combustion homogène de type HCCI (Homogeneous Charge Compression Ignition) ou combustion fortement pré-mélangée HPC (Highly Premixed Combustion).

Cependant, ces nouveaux procédés présentent encore des inconvénients non négligeables tels qu'une plage de fonctionnement zéro NOx limitée, une forte demande en gaz d'échappement recirculés (EGR) nécessitant de revoir complètement la boucle d'air tout en maintenant des performances pleine charge de bon aloi, et surtout des émissions de HC (Hydrocarbures imbrûlés) et de CO (monoxyde de carbone) élevées à faible charge.

Les technologies de distribution variable émergentes sur les moteurs peuvent changer complètement la donne concernant ces nouveaux procédés de combustion, notamment à travers les possibilités qu'elles offrent en matière d'EGR interne et de réduction du taux de compression effectif.

À travers l'exemple bien connu du concept de combustion HCCI bi-mode NADI™ développé par l'IFP, ce papier s'intéresse au potentiel d'amélioration de ce type de combustion en utilisant différentes configurations de distribution variable à l'admission et à l'échappement et compare les approches. Les résultats sont obtenus sur un moteur monocylindre doté d'un système de distribution totalement variable. Après une rapide description de ce système et des possibilités qu'il offre, deux aspects du potentiel de la distribution variable sont étudiés :

– d'une part les différents moyens d'obtenir de l'EGR interne et ses principaux intérêts en matière de forte réduction des émissions de HC et CO à faible charge en combustion homogène : jusqu'à 70 % de réduction sur le HC et 40 % sur le CO à même niveau de NOx ;
– d'autre part les possibilités offertes par la réduction du taux de compression effectif en particulier en vue d'augmenter la charge maximale atteignable en combustion bas NOx. Le potentiel dans ce domaine reste réduit du fait des richesses très élevées engendrées par la réduction du débit d'air.

Abstract — Variable Valve Actuation Systems for Homogeneous Diesel Combustion: How Interesting are They? — *With a high thermal efficiency and with low CO_2 (carbon dioxide) emissions, Diesel engines would become leader of tomorrow's transport market. However, the evolution of the regulatory constraints leads to a drastic reduction of their NOx (nitrogen oxide) and particulate emissions. Another interesting competitor to the NOx after-treatment systems is the use of new combustion concepts to*

reduce the raw emissions: homogeneous combustion (Homogeneous Charge Compression Ignition - HCCI- or Highly Premixed Combustion - HPC).

Nonetheless, such concepts present non negligible drawbacks such as a limited zero NOx operating range, huge external gas recirculation (EGR) needs which forces a complete redesign of the air path circuit maintaining a high level of full load performances, and above all excessive HC (unburned hydrocarbon) and CO (carbon monoxide) emissions at low load.

The emerging Variable Valve Actuation technologies (VVA) could totally change the deal of the new combustion processes especially through the internal EGR possibilities and the effective compression ratio reduction.

Through the well known dual mode HCCI combustion concept NADI™ developed by IFP, this paper aims at evaluating the improvement potential of this kind of combustion concept with the use of several intake and exhaust VVA configurations and makes a comparison between these approaches. The results come from a single cylinder engine equipped with a fully variable intake and exhaust VVA (camless). After a brief description of the VVA system and the possibilities offered, two aspects of the potential are studied:

- *the different ways to obtain internal EGR and its main interests with the high potential to reduce HC and CO emissions at low load in homogeneous combustion (HCCI or HPC): 70% reduction on the HC emissions, 40% on CO emissions keeping same NOx emissions level;*
- *the effective compression ratio reduction with a view to increase the maximum load with very low NOx emissions. First, the ways to reduce the effective compression ratio are presented and then, the reduced possibilities given in this field due to decrease of air flow are analysed.*

DEFINITIONS

CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Compression Ratio
DEe	Double Event exhaust
EGR	Exhaust Gas Recirculation
EVC	Exhaust valve Closing
EVO	Exhaust valve Opening
HC	Unburned hydrocarbons
HCCI	Homogeneous Charge Compression Ignition
HP IMEP	High Pressure IMEP
HPC	Highly Premixed Combustion
IGR	Internal Gas Recirculation
IMEP	Indicated Mean Effective Pressure
ISFC	Indicated Specific Fuel Consumption
IVC	Intake Valve Closing
IVO	Intake Valve Opening
LP IMEP	Low Pressure IMEP
LTC	Low Temperature Combustion
NADI™	Narrow Angle Direct Injection
NEDC	New European Driving Cycle
NOx	Nitrogen oxide
SEe	Single Event exhaust
TDC	Top Dead Center
VVA	Variable Valve Actuation
VVL	Variable Valve Lift (VVLei: VVL exhaust and intake)
VVT	Variable Valve Timing (VVTei: VVT exhaust and intake)

INTRODUCTION

Due to its high thermal efficiency, Diesel engine is known as one of the best candidates to face the future CO_2 (carbon dioxide) limitations. The challenge to Diesel engines is double. On the one hand, the NOx (nitrogen oxide) / Particulates emissions trade off has to be strongly improved maintaining low CO_2 emissions [13, 14]. On the other hand, downsizing tendencies lead to increasing specific power and torque output.

Two main ways to reduce NOx and particulates emissions are known at present. The first one is adequate after-treatments, de-NOx and Diesel Particulates Filters (DPF). These systems are developed or industrialised with some drawbacks in term of fuel economy, robustness, fuel sulphur sensitivity and costs because of their complex management strategies. Another way could be the reduction of these raw pollutant emissions; that is directly in the engine exhaust gases, without after-treatment (at least for NOx); using some HPC (Highly Premixed Combustion) combustion process [1, 3, 5-29]. As shown in Figure 1, these new combustion modes take place in a more or less homogeneous way throughout the bulk of the mixture, where thermal NOx formation and soot production are much lower than with typical conventional Diesel combustion diffusion flame.

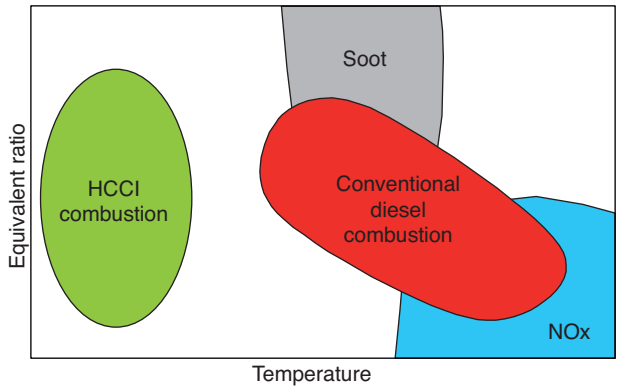

Figure 1
Area of HPC/HCCI combustion in an equivalent fuel/air ratio and combustion temperature map.

The main steps of these combustion principles are first the preparation of an air fuel mixture highly diluted by burned gases, second, the achievement of its simultaneous ignition in the whole space of the combustion chamber and third the control of such a combustion for the best performance in terms of efficiency and pollutant emissions.

However, applying HPC combustion to engines raises some difficulties:

– the zero NOx area is limited in load and speed due to the increase of Noise and smoke emissions at high load and the need of huge external EGR (Exhaust Gas Recirculation) which forces a complete redesign the air path circuit maintaining a high level of full load performances;
– the excessive HC (unburned hydrocarbon) and CO (carbon monoxide) emissions especially at low load compared to a conventional Diesel combustion.

The emerging Variable Valve Actuation (VVA) technologies could totally change the deal of these new combustion processes especially with the internal EGR possibilities (IGR) and the effective compression ratio reduction [1-3, 10, 19, 20]. Through the well known dual mode combustion concept NADI™ developed by IFP [6-8, 11, 15-18], this paper tries to evaluate on a single cylinder engine the improvement potential of these kinds of combustion concepts with the use of a completely Variable Valve Actuation system (intake and exhaust). After a brief description of the Variable Valve Actuation system used on the engine and the possibilities offered, two aspects of the potential will be studied:

– on the one hand, the different ways to obtain internal EGR and the HC and CO emissions reduction potential at low load in homogeneous combustion;
– on the other hand, the paper focuses on the effective compression ratio reduction with a view to increase the maximum load with low NOx emissions.

1 ENGINE AND VVA SYSTEM (LOTUS AVT)

The IFP single cylinder research engine used for the experimental development and testing has the following characteristics *(Fig. 2)*:

– Bore/Stroke: 87 mm/92 mm,
– Compression ratio: 14:1.

This low compression ratio allows extension of the HPC operating range at high load with a better start of combustion control by means of a longer ignition delay. This experimental engine has a four-valve single cylinder head and VVA system provided by Lotus (Lotus camless AVT system). The AVT (Active Valve Actuator) system has been fully described in [4, 5, 8, 11]. This electro-hydraulic valve actuation system has full flexible control over valve lift, timing and velocity including precision valve closing deemed necessary for complete control of each valve. The system can operate different profiles on different valves and is able to control each individual valve separately. The system can easily generate valve profiles (polynomial, triangular or trapezoidal) and up to 256 individual profiles can be stored in a useable array. As will be shown later, the system is also capable of opening and closing valves more than once per engine cycle (for example: re-opening of one or two exhaust valve(s) during the intake phase), and is limited only by hydraulic fluid delivery in terms of valve velocity and hence operating strategy.

The injection system is a second generation common rail system (Maximum injection pressure 160 MPa). The combustion system (chamber, piston bowl geometry, spray pattern and swirl level) are based on the NADI™ HPC technology. The engine is externally boosted by pressurized air and the exhaust pressure is controlled by a throttle valve. There is an external EGR circuit with an EGR cooler so as to modulate the EGR rate and temperature. The cylinder pressure is measured via a specific cooled sensor. The maximal in-cylinder pressures allowed with this engine are: 16 MPa at 4000 rpm and 15 MPa for lower engine speeds (*i.e.* 1500 rpm).

2 HC AND CO REDUCTION AT LOW LOAD

2.1 Principle: Use of IGR (Internal Gas Recirculation)

The use of internal gas recirculation (called IGR) is an effective way to reduce HC and CO emissions at low load in HPC combustion. Indeed, IGR is composed of residual hot exhaust gases which remain in the cylinder after the exhaust phase. IGR allows improving the homogenisation (with a better

Figure 2

IFP single cylinder engine and Lotus VVA system on specific cylinder head.

evaporation) after the injection and increasing the global temperature during the combustion. This has a positive effect on HC and CO emissions. Nonetheless, the combustion temperature increase has a negative impact on NOx emissions: if EGR is completely replaced by IGR, the combustion temperature is higher and the NOx emissions also increase. So IGR is generally used with EGR to reach the best trade off between NOx, fuel consumption and CO/HC emissions.

The IGR effect is assessed on two specific 1500 rpm points: IMEP (Indicated Mean Effective Pressure) 0.17 MPa and IMEP 0.37 MPa. These points are characteristic of the part of the NEDC (New European Driving Cycle) cycle where the main constraints in HPC combustion are HC and CO emissions. The different VVA configurations are tested with a constant injected quantity, injection timing (single injection) and temperature downstream EGR cooler to focus on the IGR effect on combustion. The IMEP is not constant but close respectively to 0.17 or 0.37 MPa. Table 1 gives the main parameter settings of the chosen points.

TABLE 1

Main parameters settings of the HPC chosen points for IGR effect evaluation

	1500 rpm IMEP 0.17 MPa	1500 rpm IMEP 0.37 MPa
Intake Pr. P2 (MPa)	0.101 (atm)	0.101 (atm)
Exhaust Pr. P3 (MPa)	0.112	0.112
TEGR downstr. EGR cooler (°C)	70	90
Injection Pr. (MPa)	120	120
Injected Quantity (mm^3/stroke)	8 +/- 0.5	15 +/- 0.25
Start of Inj. SOI (°CA)	15	16

2.2 Ways to Obtain IGR with VVA and Results

The completely Variable Valve Actuation system used on this single cylinder engine allows specific valve lifts to be defined in order to promote more or less internal gas recirculation. In particular, this strategy is used in heavy duty application as described in [1].

2.2.1 Re-Compression of Exhaust Gases

The idea is to close the exhaust valve before the piston reaches the TDC (Top Dead Centre) so as to keep some residual exhaust gases in the combustion chamber. In this case, the exhaust gases are re-compressed during the end of the piston stroke to TDC.

With this method, the IGR rate could be modified by varying the exhaust valve lift. Nonetheless, IGR and EGR have to be used in the same time to reach a sufficient gas recirculation value and very low NOx levels.

VVTe (Variable Valve Timing exhaust)

The exhaust gases re-compression is realized with modification of exhaust valve timings: the timing of the exhaust valve lift is advanced keeping the valve opening duration and lift constant, as shown in Figure 3.

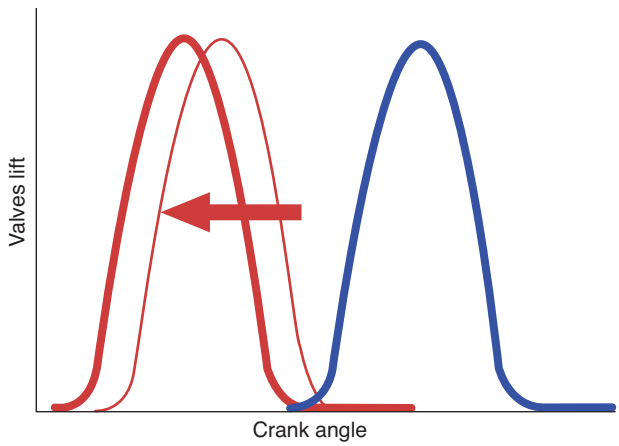

Figure 3

Internal EGR with exhaust valve timing modification.

Figure 4 presents a typical case at 1500 rpm IMEP 0.17 MPa with a 40°CA shift of the exhaust valve lift timing.

The high benefit of internal EGR on HC and CO emissions is clearly shown by these results: CO is reduced by about 20% and HC are divided by 2.

Two phenomena can explained the slight NOx increase:

- on the one hand, the increase of EGR gases temperature lowers volumetric efficiency and so reduces the CO_2 percentage enclosed in the cylinder at same equivalent ratio;
- on the other hand the temperature increase of air and EGR trapped in the cylinder and the CO_2 reduction lead to a higher peak of heat release and higher combustion temperature. This explains the small increase in Noise too.

Nevertheless, a higher external EGR rate can compensate the NOx and Noise increases without drawback on combustion on these low load points.

The ISFC increases strongly:

- the early opening of the exhaust valve reduces the expansion phase and as a consequence High Pressure IMEP is lower;
- the pressure in the combustion chamber just before the opening of the intake valve is higher (Low Pressure IMEP drawback).

VVTei (Variable Valve Timing exhaust and intake)

To compensate the LP IMEP drawback and recover part of the energy used to re-compress the exhaust gases, the exhaust valve lift timing change could be combined with a symmetric intake valve lift timing modification *(Fig. 5)*.

Figure 6 presents a typical case at 1500 rpm IMEP 0.17 MPa with two exhaust/intake valve lift timing shifts of 20 and 40°CA.

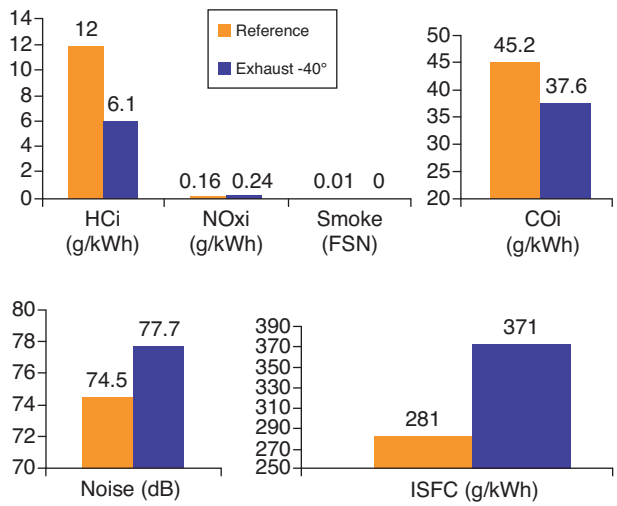

Figure 4

1500 rpm, IMEP 0.17 MPa.
Exhaust valve lift timing change of 40°CA.

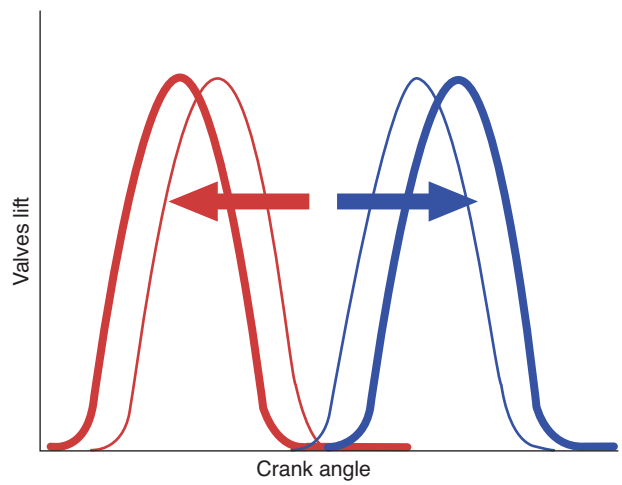

Figure 5

Internal EGR with exhaust and intake valve timing symmetric modification.

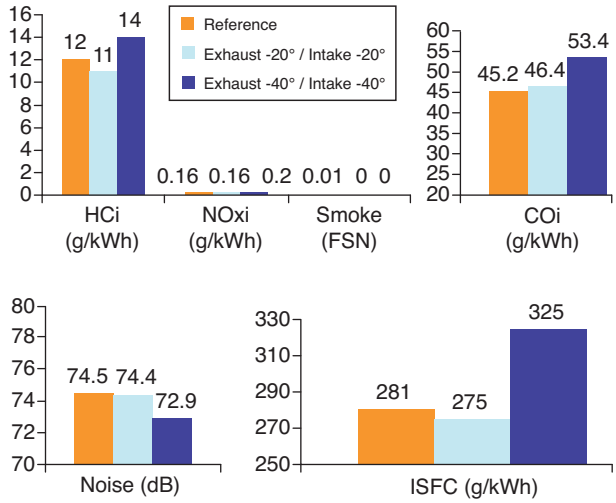

Figure 6
1500 rpm, IMEP 0.17 MPa.
Exhaust/ Intake valve lift timing shifts of 20 and 40°CA.

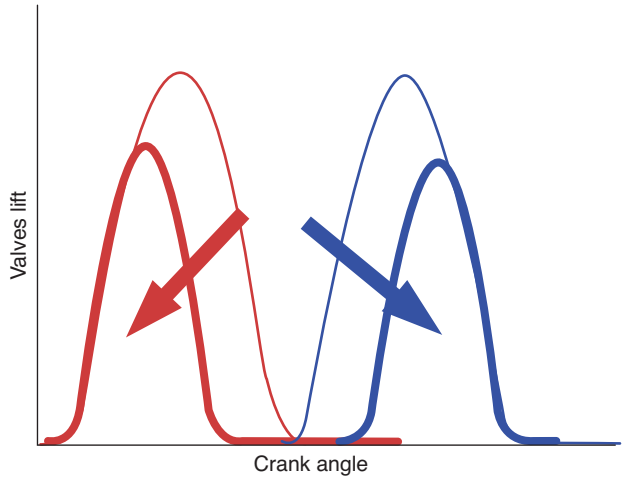

Figure 7
Internal EGR with EVO (Exhaust Valve Opening) and IVC (Intake Valve Closing) fixed.

The symmetry in the closing of the exhaust valve and opening of the intake valve allows the inside chamber recompressed gases to be expanded before opening the intake valve. This is a reason why the increase of ISFC is lower than the previous case. This leads to an increase of the Low Pressure IMEP of only 0.02 MPa on this operating point. Nevertheless, the effective compression ratio is reduced due to the later closing of the intake valve. As a consequence, HC and CO emissions increase which balances the benefit of internal EGR. Indeed, as will be described later, the reduction of the effective compression ratio and of the temperature before combustion can have a non negligible effect on the mixture formation, with an increase of the liquid film on the wall. Finally, the reduction of HC and CO emissions is very limited.

VVLei (Variable Valve Lift exhaust and intake)

In order to avoid the negative effects of expansion stroke and effective compression reduction, an alternative method consists in fixing the IVC (Intake Valve Closing) and the EVO (Exhaust Valve Opening) as shown in Figure 7.

- Fixing IVC avoids decreasing the effective compression ratio which is a drawback for HC and CO emissions, as described before
- Fixing EVO avoids opening too soon the exhaust valve and reducing the expansion phase of the gases.

In this case, in order to keep the same speed and acceleration of the valves, the valve lifts are modified. Figures 8 and 9 present two cases: 1500 rpm, IMEP 0.17 and 0.37 MPa.

The advantages in HC and CO reduction are still present: CO reduced by 30 to 50% and HC divided by 2 but with almost no increase of ISFC (less than 5%). The influence on the Noise at 0.37 MPa IMEP is due to the increase of the peak of heat release as explained before. To decrease it, a higher EGR rate would have lead to a higher equivalent ratio and less gain on CO emissions.

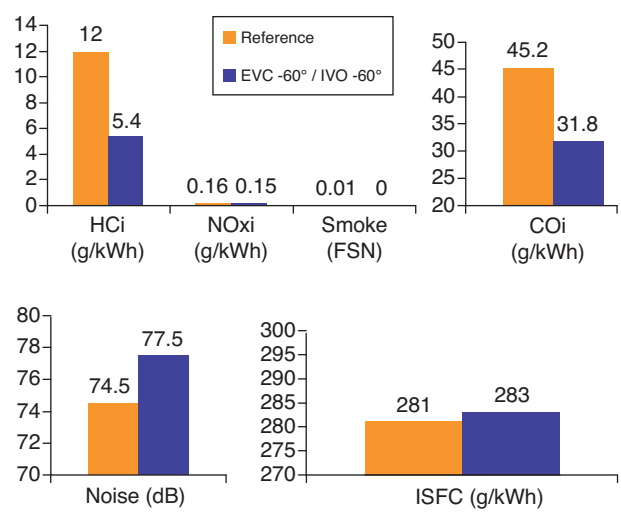

Figure 8
1500 rpm, IMEP 0.17 MPa.
EVC (Exhaust Valve Closing) / IVO (Intake Valve Opening) modification (60°CA) at same EVO/IVC.

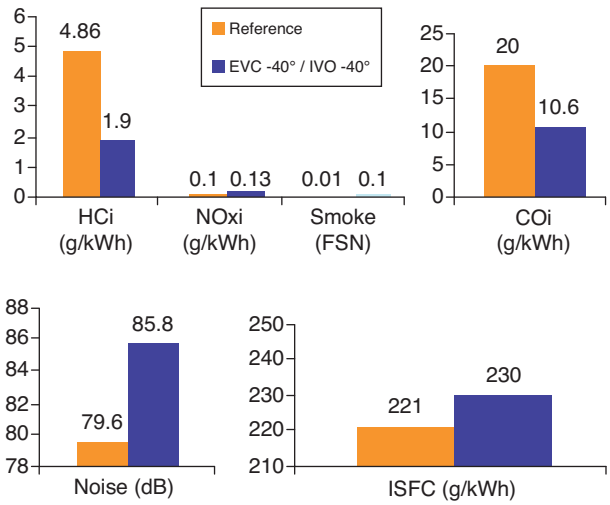

Figure 9

1500 rpm, IMEP 0.37 MPa.
EVC/IVO modification (40°CA) at same EVO/IVC.

2.2.2 Re-Opening of Exhaust Valve(s) During Intake Phase

The target is to draw the exhaust gases from the exhaust ducts and through the exhaust valve(s) during the intake phase. This method allows some exhaust gases to be re-introduced without external re-circulation and with minimum thermal and pressure losses.

DEe (Double Event of exhaust valves during intake phase)

The methodology consists in a re-opening of the two exhaust valves in the cycle, during the intake phase. Several exhaust valve lifts and timings during intake phase have been tested so as to vary the in cylinder burned gases. The tested valve lifts are presented Figure 10 below.

SEe (Single Event of exhaust valve during intake phase)

As before, the idea is to let the exhaust gases go back to the cylinder so as to promote in cylinder burned gases. As most of the constraints on HC and CO emissions are on the low speed and low load points, the target is to use one exhaust valve for the exhaust phase and the other for re-introducing the gases during intake phase with only one intake valve working during all the cycle with a view not to increase the LP IMEP. Some different configurations are tested for each valve so as to evaluate the aerodynamic effect during intake phase.

The tested valve lifts are presented Figure 11 below.

Figure 12 presents some specific results at 1500 rpm, IMEP 0.17 MPa with single and double exhaust valve re-opening. The re-opening timing of the exhaust valve affects the temperature of the recycled gases and so the HC and CO reduction. The best configuration is to have a re-opening of the exhaust valve(s) just after the TDC so as to have high temperature recycled gases. The optimal configurations chosen and shown here are:

– for the Single Event, the valve IV1 (Intake Valve close to flywheel) is not working and the valve EV4 (Exhaust valve symmetrical to IV1) is working during intake phase;

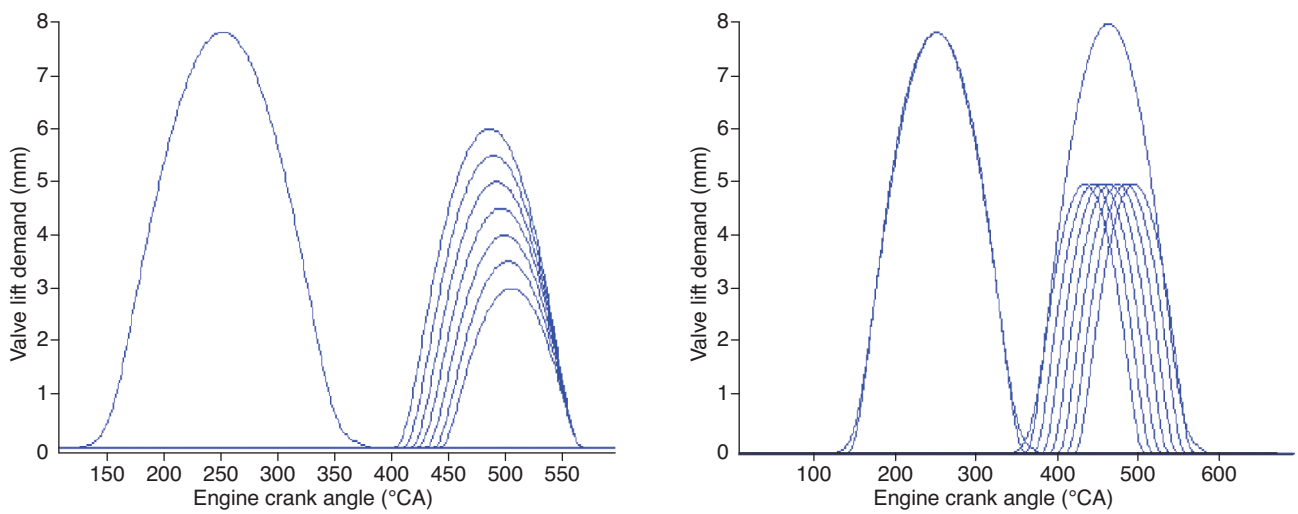

Figure 10

Valve lift modifications to re-open exhaust valves during intake phase – Double Event.

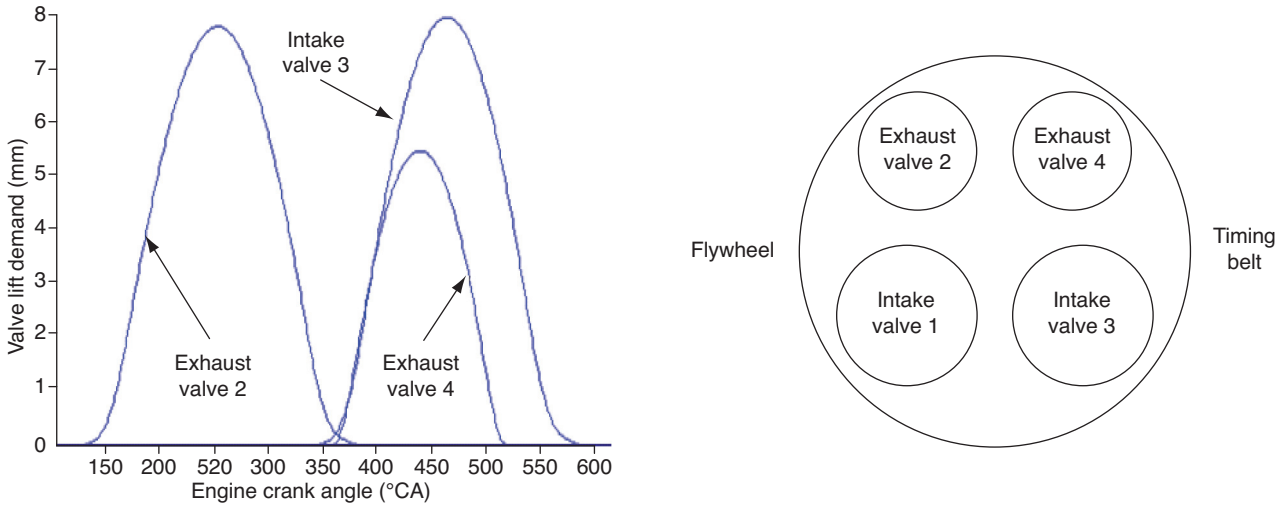

Figure 11

Valve lift modifications to re-open one exhaust valve during intake phase – Single Event.

– for the Double Event, the re-opening of the exhaust valves is just after TDC.

As before, the HC and CO reduction linked to the internal EGR is high: HC are reduced by more than 50% and CO by about 30 to 50% at same NOx level or even at lower NOx level.

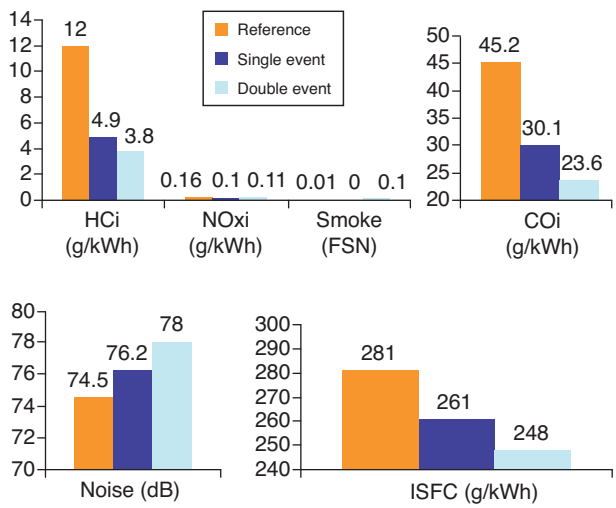

Figure 12

1500 rpm, IMEP 0.17 MPa.
Exhaust valve re-opening.
Single and Double Event.

The ISFC is not penalised by the Double Event as there is no re-compression of the exhaust gases and no reduction of the expansion phase. It is even possible to improve it *(see Fig. 13)*:

– HC and CO reduction have a positive impact on fuel consumption;
– during the re-opening of the exhaust valve(s), exhaust pressure is higher than intake pressure (about 0.01 MPa). So, the cylinder pressure increases during the intake phase which lowers the low pressure IMEP;
– the combustion efficiency is better: the increase of the cylinder pressure during intake phase and so before the beginning of combustion leads to a shorter auto-ignition delay, a better combustion timing, and a higher burnt mass fraction.

At IMEP 0.37 MPa, with an optimized re-opening of the exhaust valves (lower second exhaust lift phased later in the intake phase), the results are not exactly the same *(Fig. 14)*. The HC and CO are still highly reduced. Nevertheless, the IGR leads in this case to a volumetric efficiency reduction due to the temperature of the gases. So, the compression and combustion temperatures are higher than reference ones at same injected quantity *(Fig. 15)* and the ISFC increases slightly, due to higher thermal exchanges (10%) between 320 and 480°CA. The Noise increase is due to an earlier combustion with a higher peak of heat release *(Fig. 16)*.

2.3 Conclusion

The great flexibility of the VVA system used allows internal EGR to be promoted through many configurations. The use

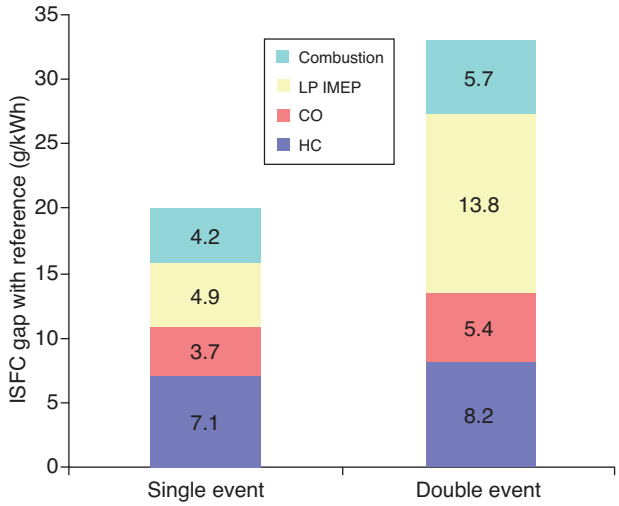

Figure 13

1500 rpm, IMEP 0.17 MPa.
ISFC gap with reference.

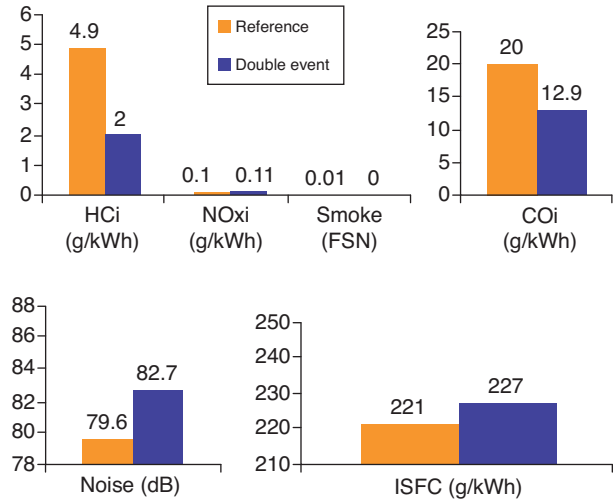

Figure 14

1500 rpm, IMEP 0.37 MPa. Exhaust valve re-opening.
Double Event.

of internal EGR is a key factor to reduce HC and CO emissions at very low load. The IGR increase (and the external EGR decrease, by difference) leads to an increase of the gas temperature in the cylinder and this has a positive impact on the mixture formation and on the combustion. It enables to reduce HC by 70% and CO by 40%. But the total mass enclosed in the cylinder at a given intake pressure is reduced. With these two phenomena, the NOx emissions increase at same equivalent ratio (same air flow). Nevertheless at very low load the equivalent ratio is low enough and it is always possible to increase the external EGR rate and to reduce NOx and Noise emissions without combustion penalty. Nonetheless, with the increase of load and equivalent ratio, the reduction of CO emissions is lower and lower at same NOx level. Finally, there is no gain on CO emissions over IMEP 0.37 MPa: the increase of EGR and equivalent ratio to

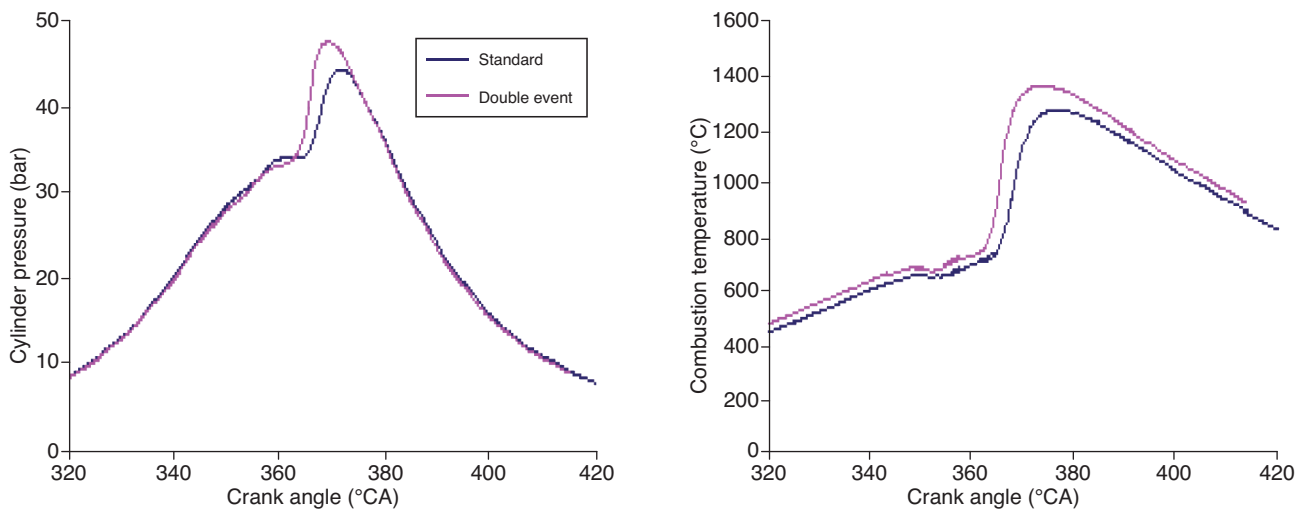

Figure 15

1500 rpm, IMEP 0.37 MPa. Exhaust valve re-opening. Cylinder pressure and temperature.

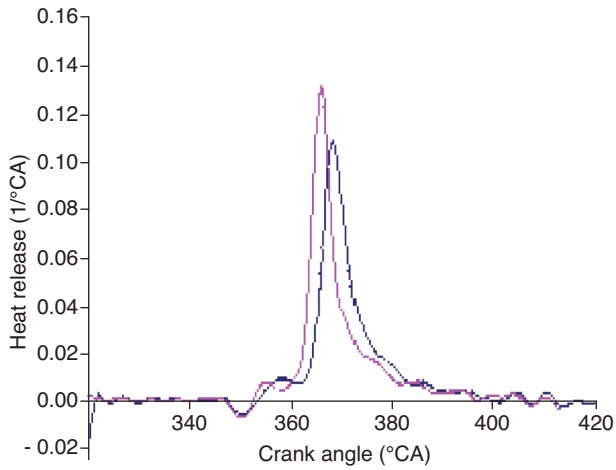

Figure 16

1500 rpm, IMEP 0.37 MPa.
Exhaust valve re-opening
Heat release.

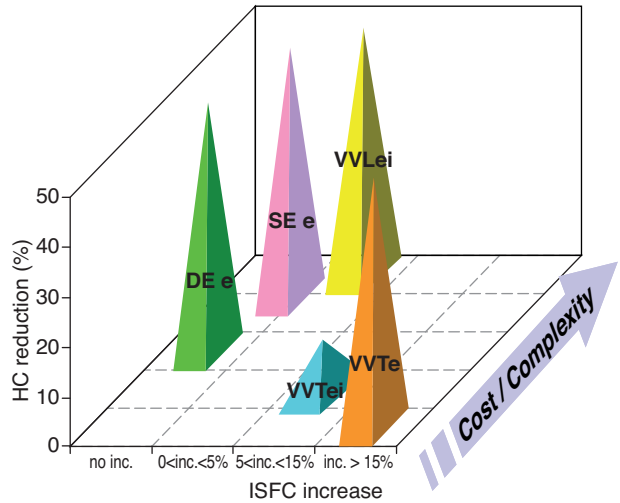

Figure 17

Trade off effectiveness / cost at very low load for each solution.

lower the NOx level finally penalizes the CO emissions and cancels the benefit of the temperature increase.

The AVT system allows many configurations to be tested on the single cylinder engine. On a multi-cylinder engine, each configuration should be obtained by a combination of specific systems to modify valve lift (multi cam systems, modification of the valve lever kinetic) and cam phasors (exhaust and/or intake). This will lead to an increase of the system complexity and cost compared to a fixed valve actuation system. So, in addition to the fact that the tested configurations do not present the same results, a specific attention must be paid to the cost of each solution. We have chosen the following parameters to classify the solutions:

– Effectiveness in HC reduction *versus* ISFC increase.
– Cost of the system represented by its complexity.

Each solution is represented in a 3D diagram. Taking a fixed valve actuation configuration (commercial configuration) as a reference, the effectiveness is represented by the HC reduction in % with the use of internal EGR (in *Z* axis) and by the correlative ISFC increase in *X* axis for low load points. The cost is represented by the system complexity in *Y* axis *(Fig. 17)*.

The first solution, VVTe is effective in HC reduction (50%) not very complex, but leads to a large increase of ISFC (>15%) due to HP IMEP (reduction of the expansion phase) and LP IMEP (opening of the intake valves with residual pressure in the cylinder) drawbacks.

The VVTei is slightly better for ISFC increase due to the opening of the intake valves after expansion of the residual gases, but not interesting for HC (about 10% reduction) whose reduction is balanced by the late intake valve closing, inducing effective compression ratio reduction. Moreover, it slightly more complex (two VVT instead of one).

The Double Event on the exhaust is more complex but it is the only one to be very effective with huge HC reduction (50%) and no fuel over-consumption: it does not change expansion phase, there is no re-compression of exhaust gases and no effective compression ratio reduction. The Single Event shows quite the same advantages (except a little higher fuel consumption) but with much more complexity due to the necessary independence of the two exhaust valves.

The two VVL system (VVLei) is the only one (with Double Event) to have practically no fuel over consumption (< 5%) by avoiding the reduction of the expansion phase and a high HC reduction (50%) but it is also the most complex.

To conclude, the Double Event on the exhaust seems to give the best trade-off between HC reduction, ISFC increase, cost of the tested solutions.

3 EXTENDING THE ZERO NOx AREA

3.1 Principle: Use of Effective Compression Ratio

Air loop technological limitations (EGR rate *vs.* turbine energy, compressor behaviour at high pressure ratio and low air flow, EGR circuit permeability and cooling capacity) and combustion limitation (noise and particulates emissions, torque reserve at high equivalent ratio) limit HPC combustions load range. The geometric compression ratio reduction

has a clear effect on NOx and Noise because of the reduction of the compression temperatures and pressures. But reducing geometric compression ratio leads to specific systems and high cost technology.

The target here is a reduction of the effective compression ratio (*i.e.* the volumetric compression ratio) with a change in the intake valve closing. This theoretically allows a decrease of the EGR rate. Nevertheless, as air mass in the cylinder is decreasing, there is a clear competition between the decrease of equivalent ratio linked to the lower EGR rate required to reduce NOx emissions and the increase of equivalent ratio due to the reduced air flow. So the benefit of lowering the effective compression ratio is not so clear and has to be assessed for different points.

3.2 Way to Reduce Effective CR with VVA

The effective compression ratio is directly linked to the volume *V* into the cylinder when the intake valve is closed. The compression affects only this volume and not the whole engine displacement. With an earlier or a later intake valve closing than the reference one, the volume *V* is modified which leads to an effective compression ratio reduction. Figure 18 below describes the different intake valve lifts used for this part of the study. They are designed taking into account the mechanical constraints of a conventional valve actuation system: to limit speed and acceleration values, the maximal lift is reduced when the duration is reduced. Figure 19 gives the effective compression ratio value regarding IVC modification.

3.3 Tested Points

The main parameters settings for the two chosen points 1500 rpm, IMEP 0.67 MPa and 2500 rpm, IMEP 0.7 MPa are described in Table 2.

TABLE 2

Main parameters settings of the HPC chosen points for IVC effect evaluation

	1500 rpm IMEP 0.67 MPa	2500 rpm IMEP 0.7 MPa
Intake Pr. P2 (MPa)	0.13 / 0.14	0.16
Exhaust Pr. P3 (MPa)	0.14 / 0.15	0.17
TEGR downstr. EGR cooler (°C)	90 +/- 10	100 +/- 10
Injection Pr. (MPa)	160	160
Injected Quantity (mm^3/stroke)	28 +/- 1	30.5 +/- 0.5
Start of Inj. SOI (°CA)	3.5	8
IVC variation (°CA)	–60; + 60	–40; + 80

3.3.1 1500 rpm, IMEP 0.67 MPa

Above this load, keeping zero NOx emissions leads to some drawbacks in terms of smoke, noise, CO emissions or efficiency.

To better understand the effect of effective compression ratio reduction on engine behaviour, the different valve lifts are tested at constant injected quantity, injection timing and temperature downstream EGR cooler. The IMEP is

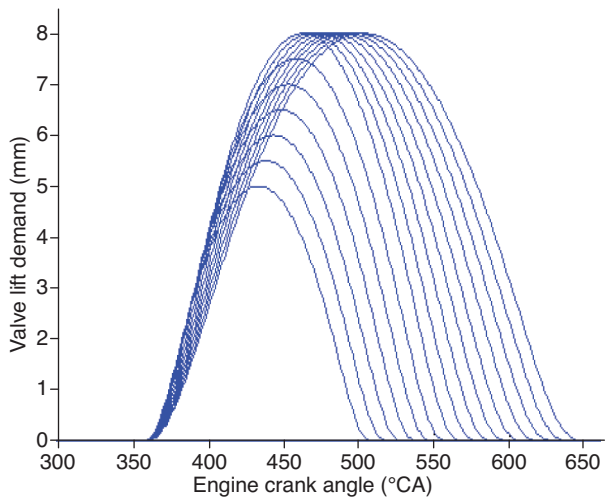

Figure 18

Intake valve closing variation to modify effective compression ratio.

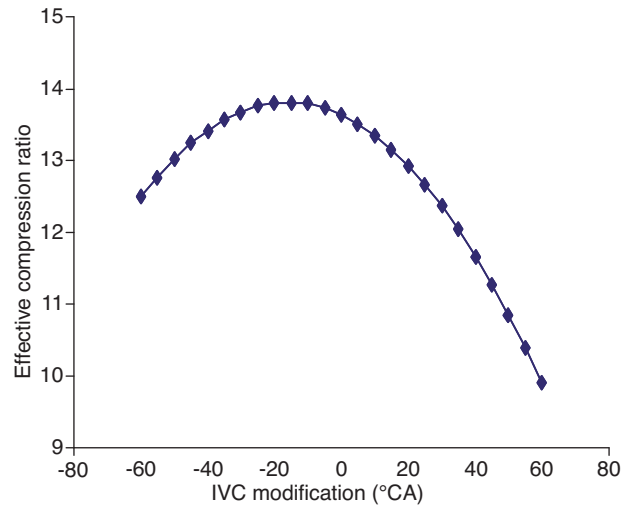

Figure 19

Effective compression ratio regarding IVC modification (0: reference IVC).

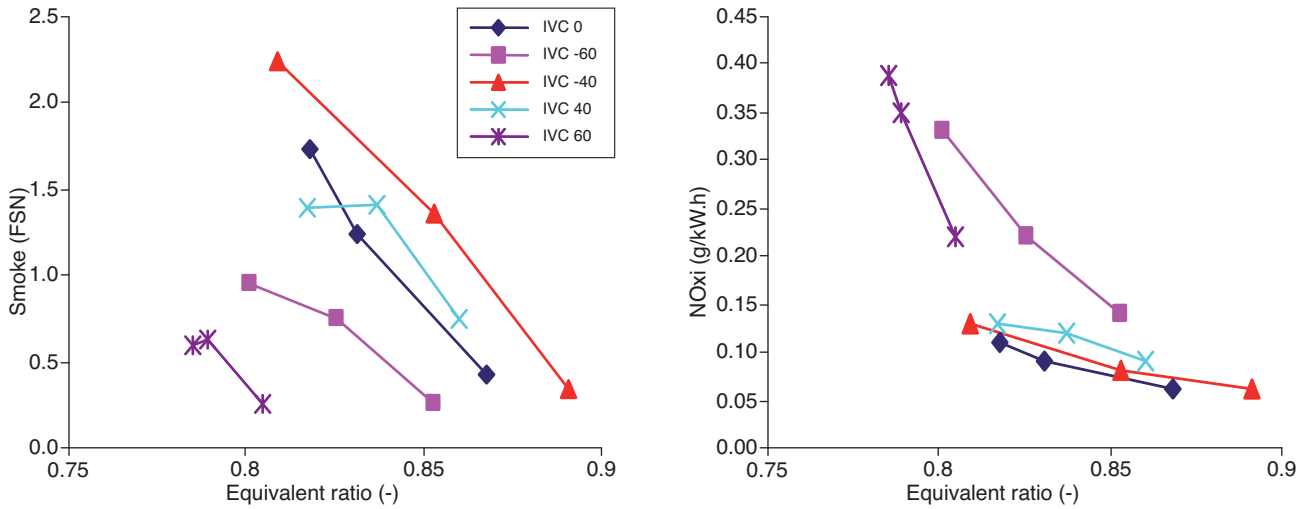

Figure 20

1500 rpm, IMEP 0.67 MPa. NOx and smoke emissions. IVC variation.

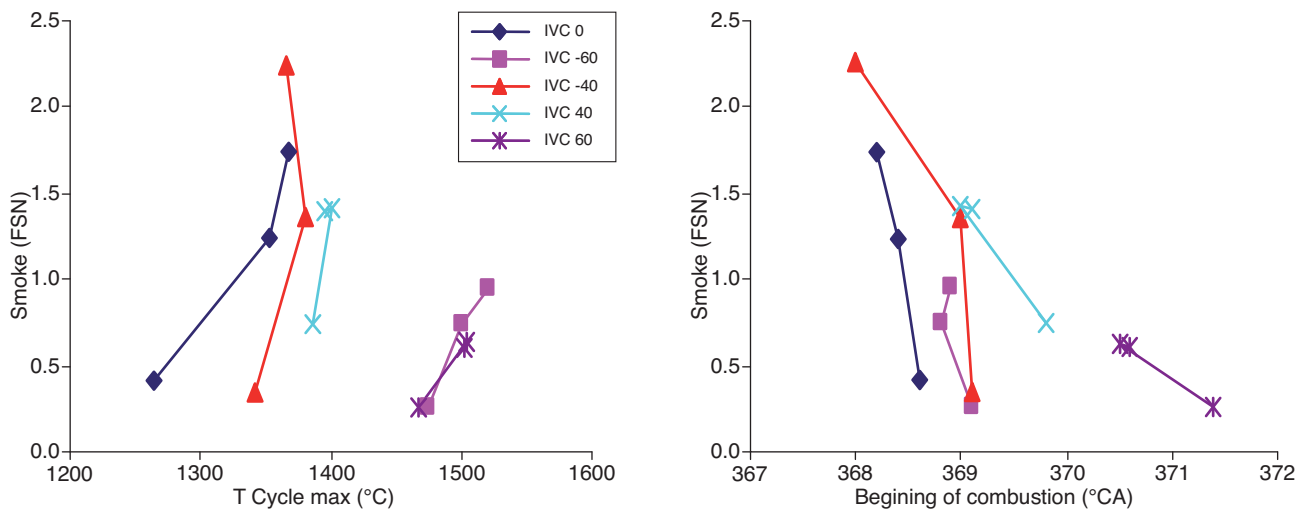

Figure 21

1500 rpm, IMEP 0.67 MPa. Smoke emissions *versus* maximum cycle temperature and beginning of combustion (auto-ignition delay).

not constant but close to 0.67 MPa. The EGR rate is adjusted as a function of the volumetric efficiency of the engine.

3.3.2 2500 rpm, IMEP 0.7 MPa

To understand the engine speed effect, the influence of effective compression ratio reduction is evaluated at around the same load as the previous point but at 2500 rpm.

As before, a constant injected quantity is applied (with an IMEP close to 0.7 MPa); injection timing and temperature downstream EGR cooler are constant. The injection strategy, with only one injection leads to high smoke level and is not suitable for the existing standards which are more based on a split injection strategy. Nevertheless, the use of only one injection avoids the problems of repartition of injected quantities between two injections so as to concentrate on the effective compression ratio influence.

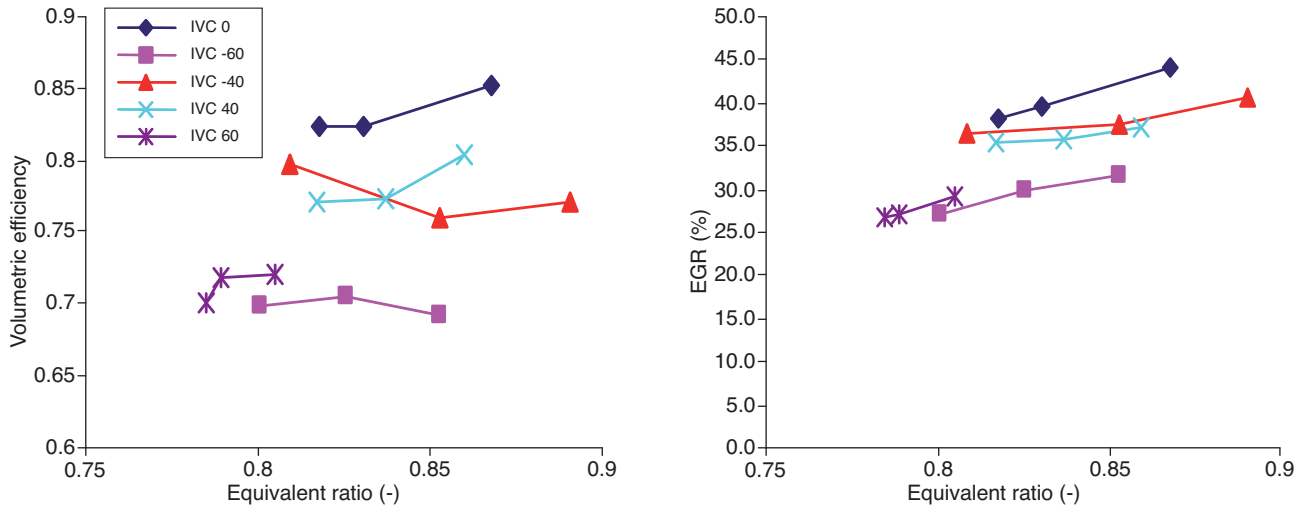

Figure 22

1500 rpm, IMEP 0.67 MPa. EGR and volumetric efficiency. IVC variation.

3.4 Results

3.4.1 1500 rpm, IMEP 0.67 MPa

Figure 20 presents the NOx and smoke emissions for the positive and negative evolutions of IVC and EGR variations (represented by the equivalent ratio variation) at a given intake pressure.

At the same equivalent ratio, the lowest NOx emissions are obtained with the standard IVC. For the highest IVC variation (positive or negative), the NOx emissions increase significantly. Smoke emissions increases at small IVC variation (40 or – 40°CA) but there is a strong decrease for the highest IVC variations.

As usual in HCCI or LTC combustion, the increase of EGR rate allows decrease of the NOx and smoke emissions (due to lower combustion temperature and longer ignition delay) whatever the IVC.

In order to understand the smoke behaviour, the auto-ignition delay and the mean cycle temperature have been computed. Figure 21 shows the smoke emissions against these two computed parameters. On the one hand, the reduction of the mass trapped in the cylinder increases the cycle temperature and could explain the increase of the smoke emissions, but on the other hand, the longer auto-ignition delay promotes the air/fuel mixture and so reduces smoke. Thus, it seems that in a first step, for the low IVC variation, the higher temperature is preponderant and so the smoke increases. In a second step, when reducing more and more the effective compression ratio, the auto-ignition delay becomes preponderant and the smoke decreases.

As shown in Figure 22, the volumetric efficiency is driven downward with the IVC variation and so, at same equivalent ratio and same intake pressure, the EGR rate is lower. This explains the NOx evolution. Thus, to keep same NOx emissions, it is necessary to increase the EGR rate and consequently the equivalent ratio.

Figure 23 shows the HC and CO emissions with effective compression ratio reduction. Although the combustion analysis shows higher mean combustion temperature for these points *(Fig. 24)*, HC and CO emissions are worse at low effective compression ratio. This could be explained by the pressures and temperatures during the injection phase: the reduction of the effective compression ratio and so of the temperature before combustion can have a non negligible effect on the mixture formation, with an increase of the liquid film on the wall.

Another important result is the large increase of the exhaust temperature *(Fig. 25)*. The effective compression ratio reduction linked to the volumetric efficiency reduction leads to the total in-cylinder mass reduction and can explain this increase. Coupled with a lower EGR demand, this phenomenon allows the increase of the energy on the turbine and so the intake pressure *(Fig. 26)*.

Figure 27 summarizes the results obtained in the best case (IVC +40 and IVC –40°CA) with the two intake pressures: 0.13 and 0.14 MPa. The NOx value is the same in all the cases: 0.12 g/kWh.

With the basic intake pressure (0.13 MPa), the reduction of effective compression ratio leads to a decrease of smoke and noise at the same NOx level. Nevertheless the cycle

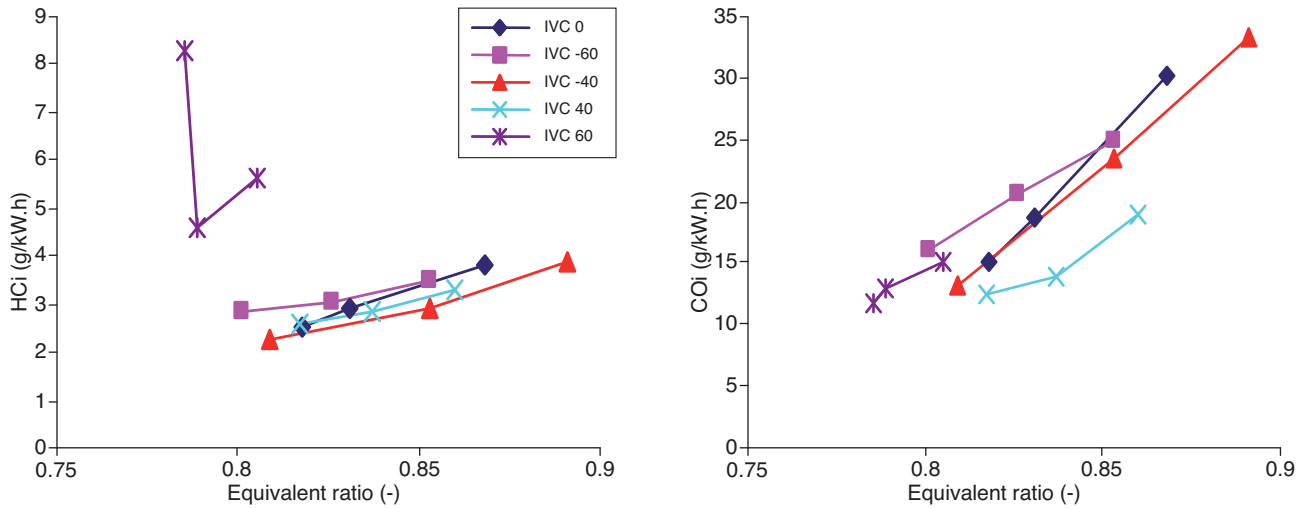

Figure 23

1500 rpm, IMEP 0.67 MPa. HC and CO emissions. IVC variation.

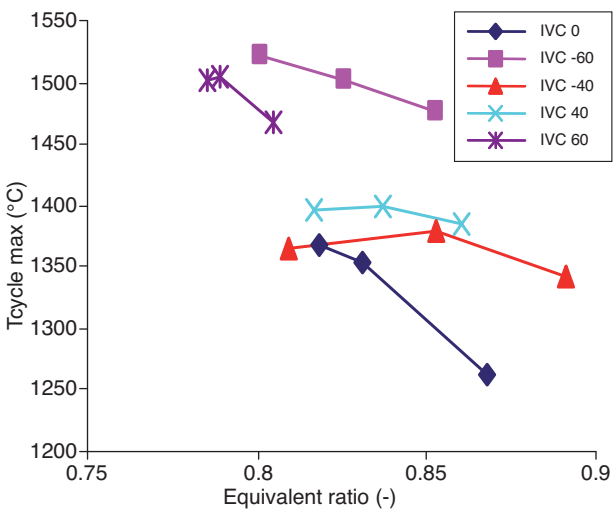

Figure 24

1500 rpm, IMEP 0.67 MPa. Maximum temperature during combustion. IVC variation.

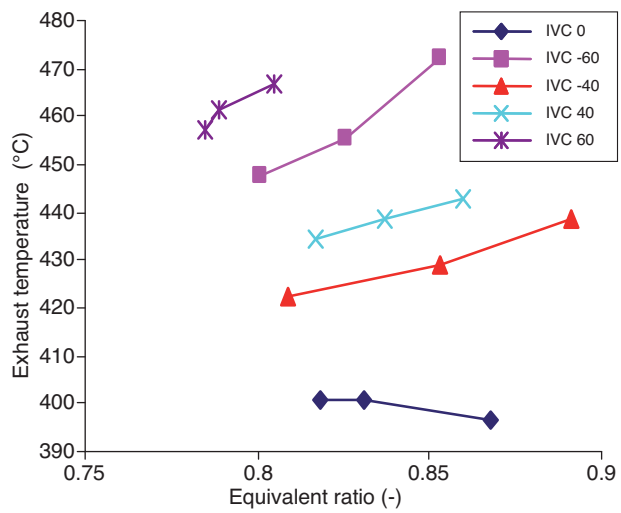

Figure 25

1500 rpm, IMEP 0.67 MPa. Exhaust temperature. IVC variation.

efficiency is worse and the reduction of the air mass impacts the equivalent ratio and increases unburned fuel (HC and CO) and thus fuel consumption. Increasing intake pressure allows a large reduction of CO and HC emissions but still with a slight drawback for ISFC compared to reference at the same intake pressure and it leads to an increase of smoke.

Thus, the effective compression ratio reduction benefit is not clear at this stage.

3.4.2 2500 rpm, IMEP 0.7 MPa

Figures 28 and 29 present the results obtained with a NOx emissions level of 0.1 g/kWh (except for the IVC +60°CA where it was not possible to achieve lower than 0.12 g/kWh of NOx). The EGR is adjusted to maintain this level and as a consequence, the equivalent ratio is set between 0.83 and 0.85.

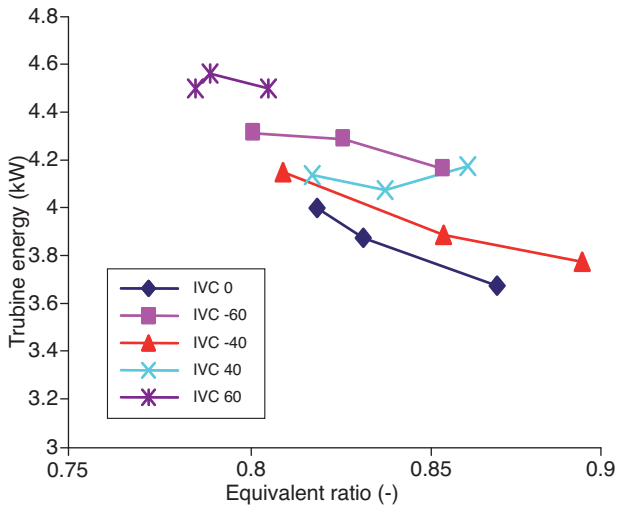

Figure 26

1500 rpm, IMEP 0.67 MPa. Turbine energy. IVC variation.

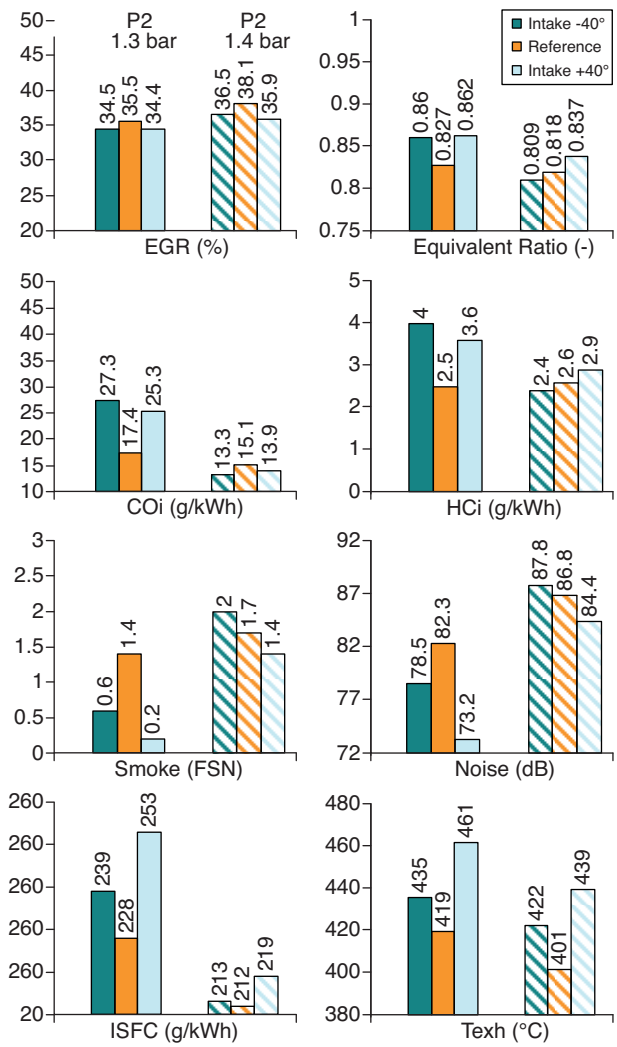

Figure 27

1500 rpm, IMEP 0.67 MPa. Summary IVC variations.

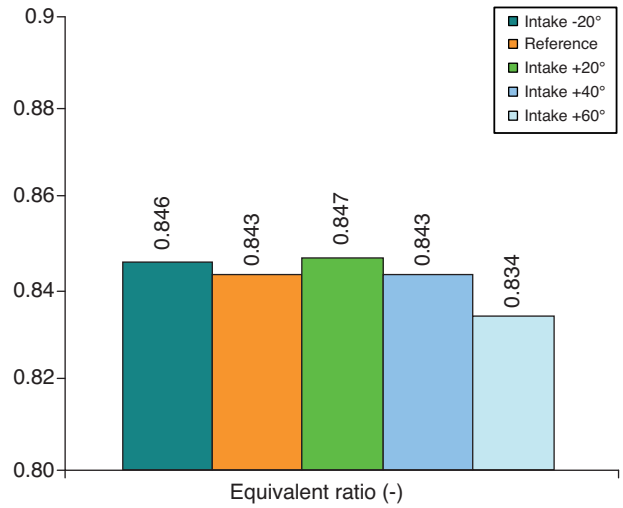

Figure 28

2500 rpm, IMEP 0.7 MPa. Equivalent ratio. IVC variation.

As at 1500 rpm, the volumetric efficiency is affected by the IVC variation. An earlier intake valve closing is worse than a later one, due to the pumping losses at the end of the intake stroke.

The HC and CO emissions are generally lower with reduced effective compression ratio. This can be explained by the increase of the combustion temperature which is higher due to the reduced total trapped mass.

The reduced effective compression ratio has a positive impact on the smoke emissions, but the level remains high except for the IVC +60°CA. This setting is also interesting for the Noise, CO and HC emissions, but presents some drawbacks for ISFC. It seems to show that with a lower equivalent ratio (but higher NOx emissions) the NOx/Smoke/Noise trade off is better.

As before, exhaust temperature increases with the reduction of the trapped mass could be interesting for the turbine energy.

Nevertheless, here again, the reduction of the effective compression ratio does not strongly improve a lot the results.

3.5 Conclusion

The effective compression ratio reduction thanks to the IVC variation is not a good solution to increase the zero NOx area. Figure 30 summarizes the conclusions of the observed effects.

The main problem with the effective compression ratio reduction is its trade-off which leads sometimes to opposite

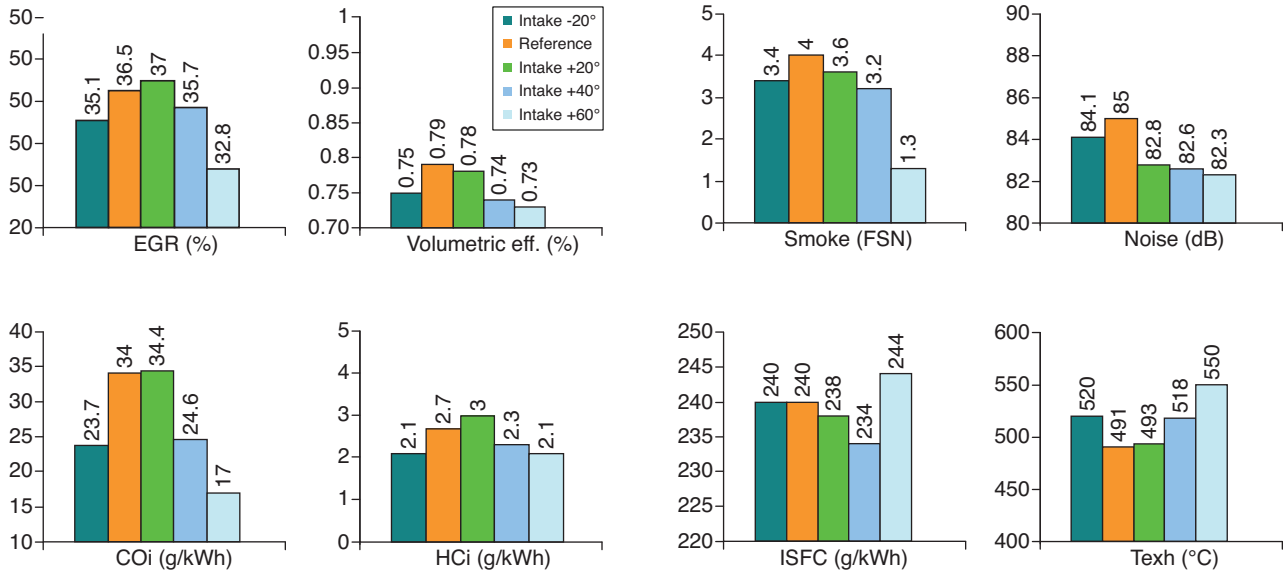

Figure 29

2500 rpm, IMEP 0.7 MPa. Summary of the results. IVC variation.

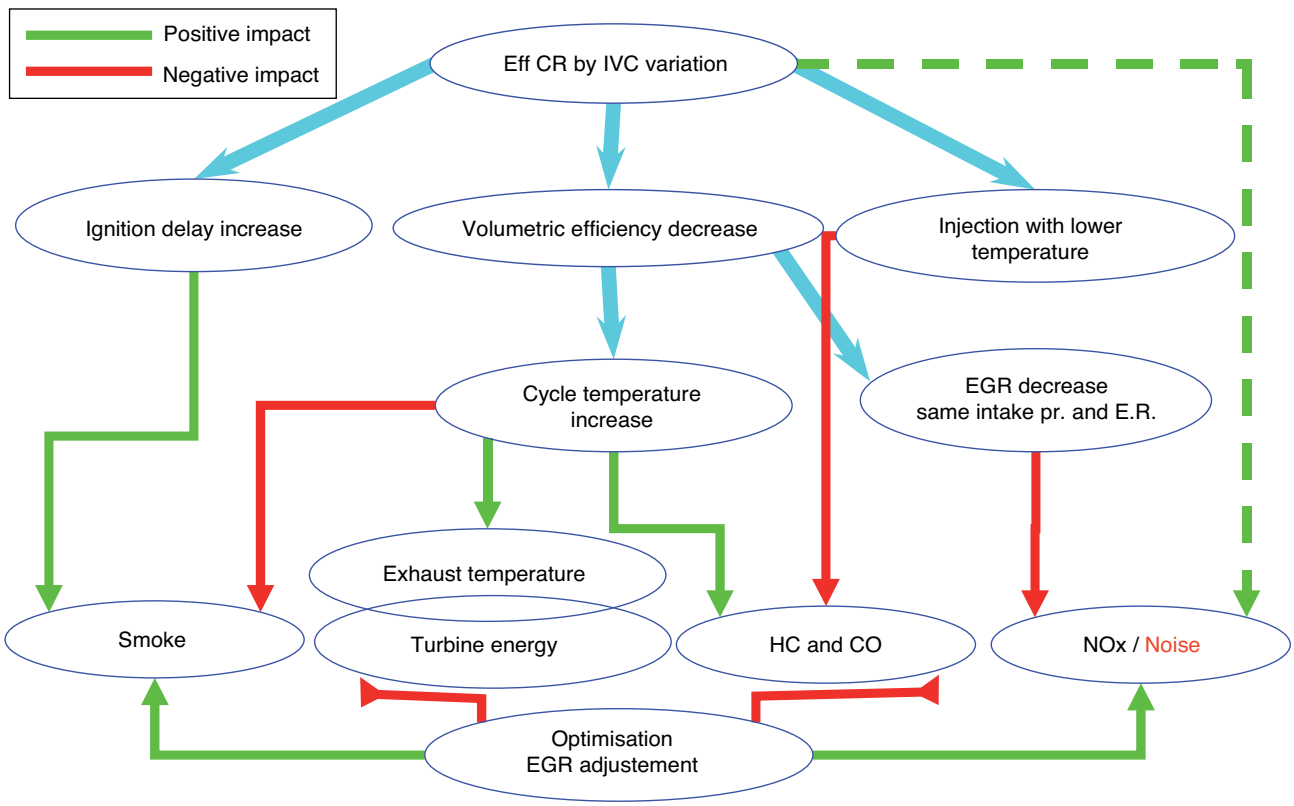

Figure 30

Summary of trade off with the effective compression ratio reduction.

results, and the final effect is not necessary positive. In Figure 30, the green arrows indicate a positive effect on the results and the red a negative one. The effective CR reduction by IVC variation should have a positive effect on NOx thanks to thermodynamic aspects (temperature and pressure decrease). But a main effect is the volumetric efficiency decrease with as a consequence an EGR rate decrease at a given intake pressure and equivalent ratio and so an increase of the NOx and Noise emissions. For the smoke, there is a similar trade off: the volumetric efficiency decrease promotes a cycle temperature increase which intensifies the smoke level but at the same time, the effective CR reduction increases the ignition delay and so has a positive effect on the premixed combustion and so on the smoke level. For HC and CO, the cycle temperature increase allows a reduction of these emissions but the effective CR reduction induces a decrease of the temperature during injection phase and so a lower vaporization which has a negative effect. One can note that cycle temperature increase has a beneficial effect on exhaust temperature and finally allows the increase of turbine energy. So, there are numerous trade-offs and the optimisation of the points through for example an EGR increase to lower NOx and smoke could lead to higher level of HC, CO and ISFC.

The final NOx / Smoke / Noise / ISFC trade off is not better than the one obtained with the reference configuration.

CONCLUSION

This paper aims at evaluating the improvement potential of the HPC combustion concept with the use of several intake and exhaust VVA configurations and makes a comparison between these approaches on a single cylinder engine. Two aspects of the potential have been studied:

- on the one hand, the different ways to obtain internal EGR and its main interests with the high potential to reduce HC and CO emissions at low load in homogeneous combustion: 70% reduction on the HC emissions, 40% on CO emissions keeping same NOx emissions level.

The tested configurations do not present the same results. Moreover, specific attention must be paid to the cost of each solution. The Double Event on the exhaust seems to give the best trade off between HC reduction, ISFC increase and cost;

- on the other hand, the paper focuses on the effective compression ratio reduction with a view to increase the maximum load with low NOx emissions. But finally, due to the reduction of total mass trapped inside the cylinder and the limit equivalent ratio in the studied cases, the reduction of the compression ratio is not seen as a potential solution to increase the zero NOx area.

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REFERENCES

1 Agrell F., Angstrom H.E., Eriksson B., Wikander J., Linderyd J. (2005) Control of HCCI During Engine Transients by Aid of Variable Valve Timings Through the use of Model-Based, Non-Linear Compensation, SAE SP-1963.

2 Fessler H., Genova M. (2004) An Electro-Hydraulic 'Lost Motion' VVA System for a 3.0-Liter, SAE SP-1898.

3 Anca R., Wagner U., Velji A., Spicher U. (2004) HCCI-A Possible Solution to Avoid Particulate/NOx Trade-Off for Future Compression Ignition Engines, CONAT20042029.

4 Turner J.W.G., Kenchington S.A., Stretch D.A. (2004) Production AVT development: Lotus and Eaton's electrohydraulic closed-loop fully variable valve train system. *25th International Wiener Motorensymposium*, Vienna.

5 Milovanovic N., Blundell D., Turner J., Duret P., Gatellier B., Monteiro L., Miche M., Zima P., Anca R., Marotraux D., Guezet J., Spinnler F., Zhao H., Perotti M., Araneao L. (2004) The use of Fully Variable Valve Train to investigate Valve Events for HCCI in High Speed Direct Injection Diesel Engines, ATA Paper 04A5017.

6 Ranini A., Potteau S., Gatellier B. (2004) New developments of the NADI™ concept to improve operating range, exhaust emissions and noise. *THIESEL 2004 Conference on Thermo- and Fluid Dynamic Processes in Diesel Engines*, Valence.

7 Walter B., Monteiro L., Miche M., Gatellier B. (2004) Improvement of Exhaust and Noise Emissions of the NADI™ Concept Using Pre-Mixed Type Combustion with Multiple Stages Injection, *2004 SIA Congress: The Diesel Engine: today and tomorrow*, Lyon, 12-13 May 2004.

8 Duret P., Gatellier B., Monteiro L., Miche M., Zima P., Maroteaux D., Guezet J., Blundell D., Spinnler F., Zhao H., Perotti M., Araneo L. (2001) Progress in Diesel HCCI Combustion within the European SPACE LIGHT Project, SAE Paper 2004-01-1904.

9 Cowland C., Gutmann P., Herzog P.L. (2004) Passenger Vehicle Diesel Engines for the US, SAE paper 2004-01-1452.

10 Lancefield T. (2003) The influence of variable valve actuation on the part- load fuel economy of a modern light-duty diesel engine, SAE, SP-1752.

11 Duret P., Gatellier B., Monteiro L., Miche M., Zima P., Maroteaux D., Guezet J., Blundell D., Spinnler F., Zhao H., Perotti M., Araneo L. (2003) Innovative diesel HCCI combustion process for passenger cars: the European SPACE LIGHT project. *EAEC Congress*, Paris, 2003.

12 Kahrstedt J., Behnk K., Sommer A., Wormbs T. (2003) Combustion Processes to meet future emission standards, MTZ 10/2003.

13 Weissbäck M., Csato J., Glensvig M., Sams T., Herzog P. (2003) An approach for future HSDI Diesel Engines, MTZ 9/2003.

14 Umwelt Bundes Amt. (2003) Future Diesel - Exhaust gas legislation for passenger cars, light-duty commercial vehicles, and heavy duty vehicles - Updating of limit values for Diesel vehicles, www.umweltdaten.de/uba-info-presse/ hintergrund/ FutureDiesel_e.pdf.

15 Walter B., Gatellier B. (2003) Near Zero NOx Emissions and High Fuel Efficiency Diesel Engine: the NADI™ Concept Using Dual Mode Diesel Combustion, *Oil Gas Sci. Technol.* **58**, 1, 101-114.

16 Gatellier B., Walter B. (2002) Development of the High Power NADI™ Concept Using Dual Mode Diesel Combustion to Achieve Zero NOx and particulate Emissions. *Thiesel 2002 Conference on thermo - and fluid Dynamic Processes in Diesel Engines*, Valence.

17 Walter B., Gatellier B. (2002) Development of the High Power NADI™ Concept Using Dual Mode Diesel Combustion to Achieve Zero NOx and Particulate Emissions, SAE paper 2002-01-1744.

18 Gatellier B., Ranini A., Castagné M. (2006) New Developments of the NADI™ Concept to improve Operating Range, Exhaust Emissions and Noise, Concept Using Dual Mode Diesel Combustion, *Oil Gas Sci. Technol.* **61**, 1, 7-23.

19 Sommer A., Stiegler L., Wormbs T., Kabitzke J., Buschmann G. (2006) Will we need variable valve trains for passenger-car diesel engines in the future? *SIA Variable Valve Actuation Conference*, IFP Rueil-Malmaison, 30 November 2006.

20 Kapus P., Fraidl G., Sams T., Kammerdiener T. (2006) Potential of VVA Systems for Improvement of CO_2, Pollutant Emission and Performance of Combustion Engines. *SIA Variable Valve Actuation Conference*, IFP Rueil-Malmaison, 30 November 2006.

21 Hultqvist A., Engdar U., Johansson B., Klingmann J. (2001) Reacting Boundary Layers in a Homogeneous Charge Compression Ignition (HCCI) Engine, SAE Paper 2001-01-1032.

22 Kimura S., Aoki O., Kitahara Y., Aiyoshizawa E. (2001) Ultra-Clean Combustion Technology Combining a Low – Temperature and Premixed Combustion Concept for Meeting Future Emission Standards, SAE Paper 2001-01-0200.

23 Christensen M., Johansson B. (2000) Supercharged Homogeneous Charge Compression Ignition (HCCI) with Exhaust Gas Recirculation and Pilot Fuel, SAE Paper 2000-01-1835.

24 Kimura S., Aoki O., Ogawa H., Muranaka S. (1999) New Combustion Concept for Ultra-Clean and High-Efficiency Small DI Diesel Engines, SAE Paper 1999-01-3681.

25 Christensen M., Hultqvist A., Johansson B. (1999) Demonstrating the Multi Fuel Capability of a Homogeneous Charge Compression Ignition Engine with Variable Compression Ratio, SAE Paper 1999-01-3679.

26 Richter M., Franke A., Aldén M., Hultqvist A., Johansson B. (1999) Optical Diagnostics Applied to a Naturally Aspired Homogeneous Charge Compression Ignition Engine, SAE Paper 1999-01-3649.

27 Iwabuchi Y., Kawai K., Shoji T., Takeda Y. (1999) Trial of New Concept Diesel Combustion System –Premixed Compression – Ignited Combustion, SAE Paper 1999-01-0185.

28 Odaka M., Suzuki H., Koike N., Ishii H. (1999) Search for Optimizing Method of Homogeneous Charge Diesel Combustion, SAE Paper 1999-01-0184.

29 Akagawa H., Miyamoto T., Harada A., Sasaki S., Shimazaki N., Hashizume T., Tsujimura K. (1999) Approaches to Solve Problems of the Premixed Lean Diesel Combustion, SAE Paper 1999-01-0183.

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