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Overview on the Cylinder Deactivation techniques

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Abstract. "Temporary downsizing" in the form of deactivation of the cylinders is used as an attractive compromise, as it allows to improve fuel consumption and at the same time it allows sufficient power reserve to meet the requirements of the driver, maintaining driving pleasure as well as comfort regarding noise and vibration levels.
The paper aims to present an overview on the cylinder deactivation techniques focusing on the stakes and challenges related with their implementation.
Keywords: cylinder deactivation, variable displacement, pumping losses, fuel saving, emissions reduction

1. Introduction

Within the automotive industry, currently, there are intense debates about sustainable mobility as part of the larger concept regarding sustainable development of the human society. The stated goal is to reduce global warming, caused by increased greenhouse gas (GHG) emissions, which directly influence human society, limiting the chances of natural development of future generations. At the same time, it is desired to significantly reduce the impact of the road mobility on human health by reducing pollution. Therefore, solutions are being sought to efficiently reduce CO2 emissions in the exhaust gas, which in the case of internal combustion (IC) engines means reducing fuel consumption, in other words, increasing their effective efficiency. CO2 is recognized as the main GHG, and road transport seems to contribute to more than 20% to carbon dioxide emissions, according to [1].
One of the methods used to reduce CO2 emissions is to deactivate cylinders in traffic situations where the need for engine torque to ensure road propulsion is reduced (e.g., urban traffic shown in Fig. 1). The advantage of such a solution is that the production of the necessary engine torque is done in operating conditions characterized by a higher efficiency.
Variable displacement, obtained by deactivating some cylinders, is one of the solutions recognized as having an important potential to improve the energy and environmental performance of the IC engine. Its application in series production, along with other solutions (variable compression, variable valve actuation, electrification of the powertrain, etc.) can contribute to the continued use of the IC engine as an energy source for road mobility in the coming period, characterized by high legislative pressures to reduce exhaust emissions (GHG and polluting gases).
This being the context, the paper aims to present an overview on the cylinder deactivation (CDA) techniques focusing on the stakes and challenges related with their implementation. The side effects, less pleasant, resulting from using this solution are to be also highlighted: high levels of NVH (Noise, Vibration, Harshness), high complexity and cost, low durability, etc.

2. Study of constructive solutions used for cylinder deactivation (CDA)

Passenger cars (PC) use, to a large extent, SI engines, of which the most used are those with 4 cylinders. Conventional SI engines used in PC run, for most of their operating time, on partial loads, at medium-low speeds, most often below 2000 rpm. In the urban cycle, the speeds of cars usually do not exceed 50 km/h, and the corresponding speeds are not higher than 2000 rpm [2].

"Temporary downsizing" in the form of CDA is used as an attractive compromise, as it allows to improve fuel consumption especially in situations of city driving conditions (most often encountered in PC's life), but at the same time allows sufficient power reserve to meet the requirements of the driver, maintaining driving pleasure as well as comfort regarding noise and vibration levels [3].

CDA is a technology known for its effect of improving SI efficiency at partial loads, thanks to its ability to reduce pumping losses by disabling some of the cylinders at partial loads while active cylinders are operating at higher load, thus increasing engine efficiency. Implementing a CDA strategy generally involves disabling the intake and exhaust valves in the deactivated cylinders in order to reduce pumping losses due to the "gas spring" effect of the intake air [4].

Currently, in order to control the engine load, a throttle plate is used to adjust the amount of air flowing towards the cylinders – it is what is usually called as a quantitative load control method. However, the throttle plate causes a reduction of the absolute in-cylinder pressure, which leads to considerable losses due to the pumping effect and low combustion efficiency. For these reasons, fuel consumption becomes poor. When CDA is used at partial loads, the active cylinders operate at a higher load to maintain a constant engine load. In this way, a higher cylinder pressure is achieved, as well as a greater opening of the throttle valve, thus reducing pumping loss and fuel consumption [4] as shown in Fig. 1.

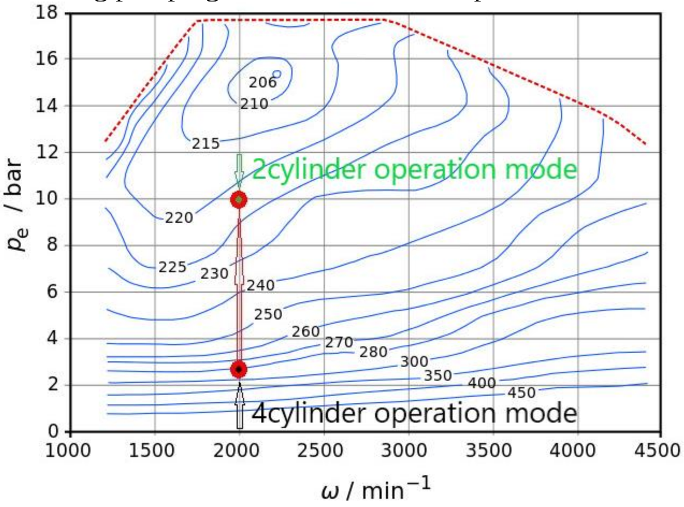

Figure 1. Effect of CDA on operation points over Brake Specific Fuel Consumption of a 4 cylinder SI engine [5]

2.1 Technical solutions that allow cylinder deactivation (CDA)

2.1.1. Sturtevant

The first implementation of Cylinder Deactivation was found on the Sturtevant 38 / 45HP 6-cylinder car, produced in 1905, in Boston, Ma. [6]. The driver could deactivate 3 cylinders, by stopping one of the magnetos and permanently opening the exhaust valves on the respective cylinders [7]. The efficiency of this system is not known, but it is considered the pioneer of CDA techniques.

2.1.2. Enger

Enger Twin-Unit Twelve debuted in 1917, with a 3.7l 60° V12 engine with a lever on the steering column, which once operated, kept the exhaust valves open on one of the two banks of 6 cylinders, in order to avoid compression and at the same time, close the intake manifold on the same side of the engine [8].

2.1.3. GM

In 1981, General Motors (GM) introduced the 8-cylinder Cadillac Modular Displacement engine with solenoid-controlled rocker arm (shown in Fig. 2) to deactivate the intake and exhaust valves.

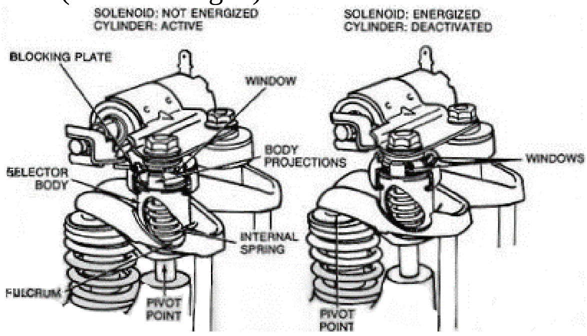

Figure 2. Cadillac V-8-6-4 Modular Displacement [9]

In 2005 and 2007, General Motors launched a 5.3L V8 and a 3.9L V6 with hydraulically deactivated valve lifters, shown in Fig. 3, to deactivate the intake and exhaust valves on half of the engine's cylinders. Displacement on Demand, as it was called, was renamed to Active Fuel Management over the years and promised a gain of 12% in fuel economy for the V8 unit.

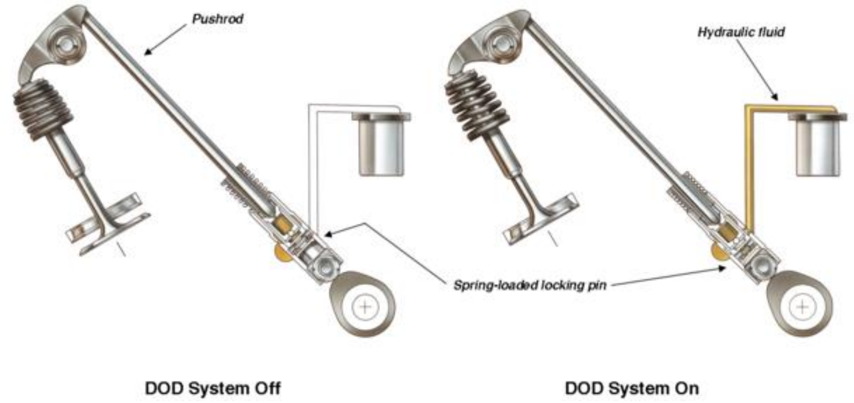

Figure 3. Displacement on Demand hydraulic lifter (deactivated on the left, activated on the right) [10]

In 2018, an improved version, called Dynamic Fuel Management, allows deactivation of 1 to 7 cylinders, depending on the need, using Dynamic Skip Fire (DSF) technology for variable CDA.

2.1.4. Mitsubishi

In 1982, Mitsubishi [11] launched the 1.4L 4-cylinder engine with variable displacement, which deactivates the intake and exhaust valves through hydraulically switching finger followers, visible in Fig. 4. The Modulated Displacement CDA system was later implemented on Mitsubishi V6 engines.

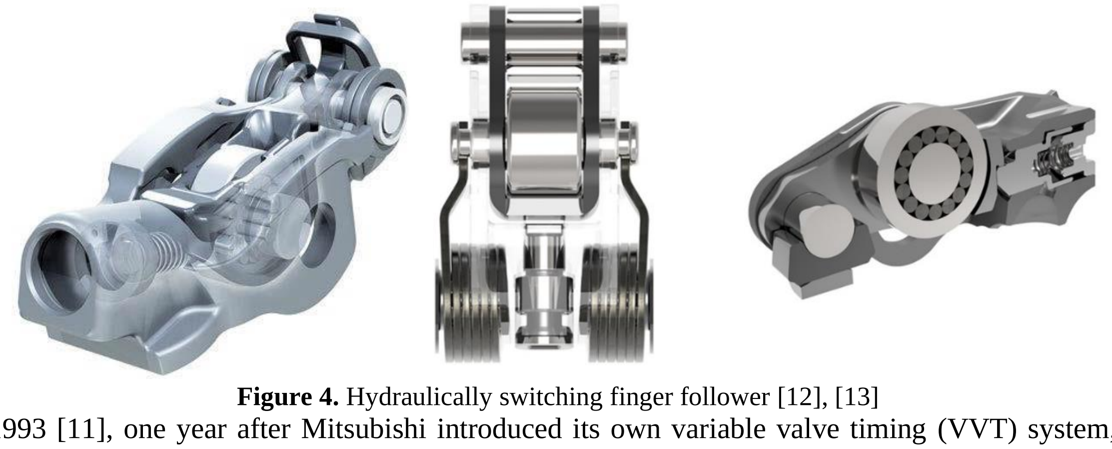

Figure 4. Hydraulically switching finger follower [12], [13]

In 1993 [11], one year after Mitsubishi introduced its own variable valve timing (VVT) system, the second generation of CDA, MIVEC-MD, was implemented. This system proved to be imperceptible during activation, and a reduction in fuel consumption of up to 20% was possible. However, Modulated Displacement was dropped in 1996.

2.1.5. Daimler Chrysler

Daimler Chrysler applied Active Cylinder Control for the first time in 2001, on a 5.8l V12 used by Mercedes-Benz, using hydraulic lifters with deactivation made by hydraulically operated bolts, shown in Fig. 6. This system was also used by Chrysler under the name of Multi-Displacement System, to deactivate the intake and exhaust valves of the 8-3-5-2 cylinders in the 5.7L V8 engine from 2004, being still used on the leads of this engine. The system was also implemented on V6 engines in the group.

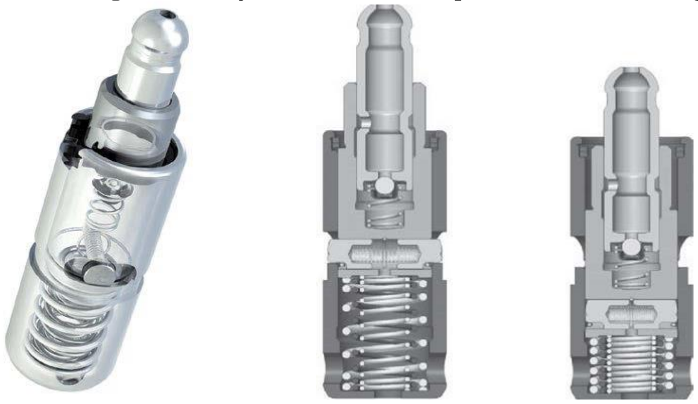

Figure 5. hydraulically deactivated lifters [12]

2.1.6. Honda

In 2008, Honda launched the 3.5L V6 variable cylinder engine (VCM) with i-VTEC system on each cylinder. The i-VTEC mechanism applies pressure to a sliding bolt to connect the rockers used to operate the valves of the respective cylinder. When the bolt is not actuated, the rocker arms do not open the valves and the cylinder is deactivated. In addition to deactivating the selected cylinders, the mechanism reduces friction losses. The system can deactivate 2 or 3 cylinders, depending on the requirement. The system is implemented on one of the cylinder banks.

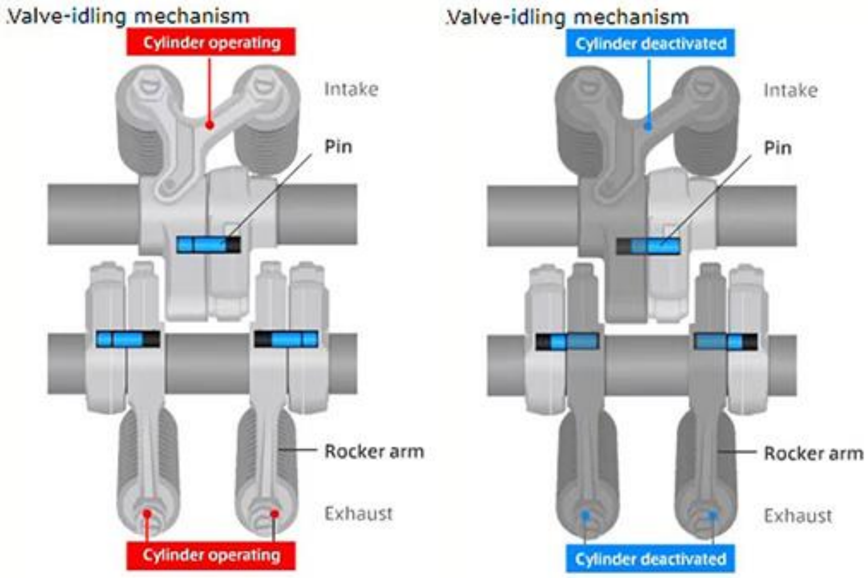

Figure 6. Honda Variable Cylinder Management [14]

2.1.7. Audi-Volkswagen

In 2012, Audi applied the Cylinder-On-Demand system to its V8 engine; the same system was applied to its 4-cylinder engine in 2013. The required valves are closed on the four camshafts with an improved version of the Audi Valvelift System (AVS). Grooved hollow shafts can slide sideways, as shown in Fig. 7, electromagnetically operated and can additionally have a "zero-opening" valve cam; because the rockers are not actuated, the valve springs keep them closed. At the same time, the engine management system stops fuel injection and ignition [15] .

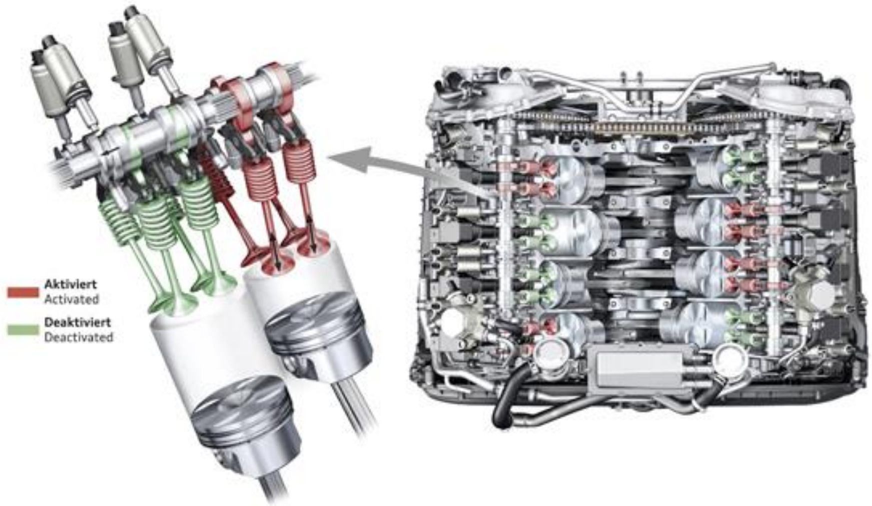

Figure 7. V8 4.0 TFSI Audi cu tehnologie Cylinder On Demand [16]

In 2013, VW introduced Active Cylinder Technology (ACT) in its 1.4 TSI engine [17]. Four solenoids, visible in Fig. 8, above cylinders 2 and 3 control the axial displacement of the camshaft to switch from the normal cam profile to the "zero-opening" using grooves on the shaft which also allows to confirm the activation mode of the cylinder deactivation system.

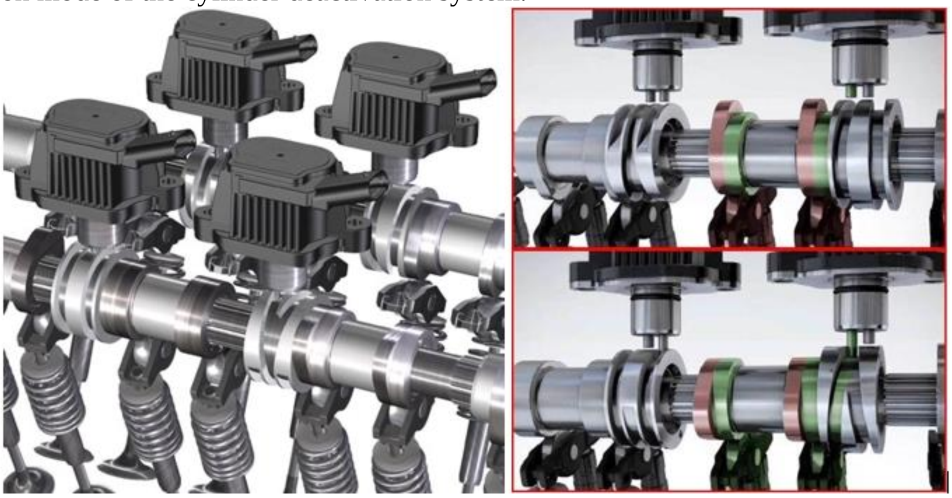

Figure 8. Deactivation units on cylinders 2 and 3 on 1.4 TSI VW Active Cylinder Technology [17]

2.1.8. Fully variable engine cylinder deactivation technology

A common feature of the technologies presented so far is the fixed number and pattern of cylinders deactivated in an engine cycle. In each of the presented CDA technologies, the engine switches from full operation mode to one or at most two variants of operation with deactivated cylinders, such as from 6 to 4 to 3 cylinders. Dynamic Skip Fire (DSF) technology does not switch to a fixed cylinder deactivation pattern but varies ignitions on the cylinders and skips continuously depending on the required load. DSF technology makes a fire / no fire decision for every cylinder on every cycle and stops the injection and at the same time disables the intake and exhaust valves accordingly [18].

Because the CDA system developed by Delphi Technologies and Tula can skip more cycles depending on request, the frequency of torque decreases and the absolute pressure in the intake manifold increases, thus pumping losses decreasing the inefficiency of combustion.

Nankyu Lee et al. [19] studied the effects of the fixed CDA and the variable CDA model on different engines mounted on different vehicles. Using the simulations compared to the results from the

experiments, it was possible to observe the differences between the two models, quantified, which varies depending on the size and number of engine cylinders, vehicle mass, load and speed used.
Schamel et al. [20] studied the implementation of CDA on the 1.0l 3-cylinder engine from Ford and concluded that Rolling Cylinder Deactivation (i.e., DSF) is the most complex method, requiring valve decoupling mechanisms on all 3 cylinders, including oil pressure required for actuators , which also leads to higher parasitic losses.

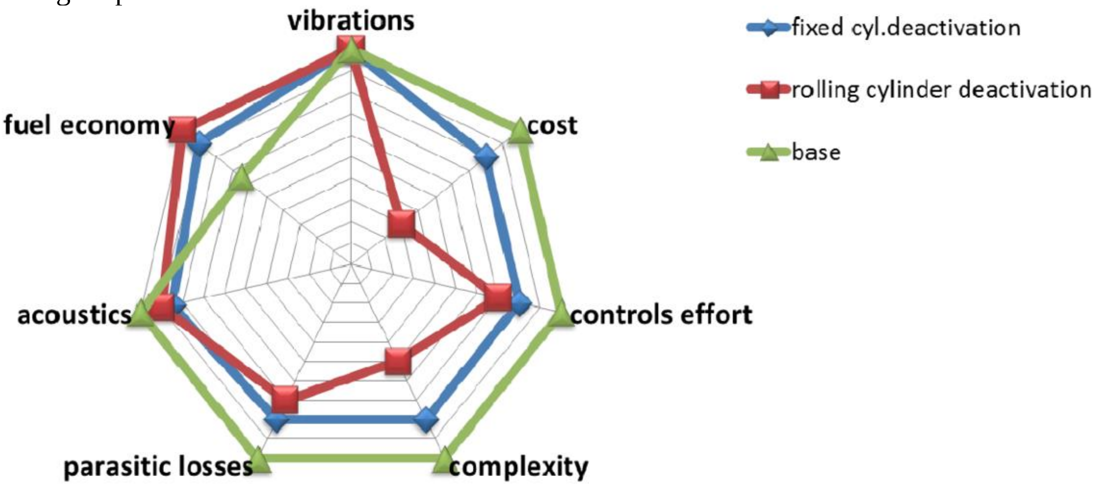

Figure 9. Comparison between fixed and rolling cylinder deactivation on 1.0l 3 cylinder engine [20]

The total benefit is in favor of the fixed CDA method on a single chosen cylinder, which presents 90% of the consumption gain for a cost of 40%, [20].
Since 2018, Ford has been producing 3-cylinder engines with CDA for cylinder 1, using hydraulically actuated lifters [21].
The variable cylinder deactivation model has a greater benefit when implemented on a high-displacement, multi-cylinder engine, taking advantage of a significant reduction in active displacement and losses resulting from pumping [19].

2.1.9. Other studied technologies

Millo et al. [4] studied the application of the CDA system on a turbocharged 4-cylinder SI engine equipped with the MultiAir Variable Valve Actuation system. Since the MutiAir system does not allow the deactivation of exhaust valves, an innovative strategy has been developed, exploiting internal exhaust gas recirculation (iEGR) in deactivated cylinders, so as to reduce their pumping losses. This strategy has proven to be effective at low loads and low revs, below a Brake Mean Effective Pressure (BMEP) of 3 bar and below 3000 rpm.
J. Zhao et al. [2] studied a strategy to combine VVT with an innovative CDA method by using 2 intake manifolds, a manifold for cylinders 1 and 4 and a manifold for cylinders 2 and 3, to improve the fuel economy of SI engines with 4 cylinders. Even though the efficiency of the two-manifold intake method is much lower than that of the classic CDA at high revs, at low loads and at low revs, the methods have similar results in terms of fuel consumption. This method is suitable for the urban cycle and does not require special technology for deactivating the cylinders or major engine modifications. The two intake manifolds require low production costs and are easy to implement.
One CDA system is made using FreeValve technology [22], which is being tested on a 1.6l Compression Ignition (CI) engine, but which can be used on any type of IC engine, it can be implemented with major benefits, the only disadvantage being the cost . FreeValve replaces the entire valvetrain system, as seen in Fig. 11, no longer using a camshaft to open the valves. The system uses electro-hydraulic-pneumatic actuators to operate each valve individually and independently, both in duration and as providing a truly fully variable valvetrain, including the ability to implement fully variable CDA technology. No longer requiring a throttle, tests to date have shown a 15% reduction in fuel consumption on the same engine. The benefits are major, especially at idle, where a 17.2% reduction in losses has been observed compared to normal operation. FreeValve is a method of implementing the variable CDA by modulating the torque according to the requirement, also overcoming the risk of knocking at high speeds and loads.

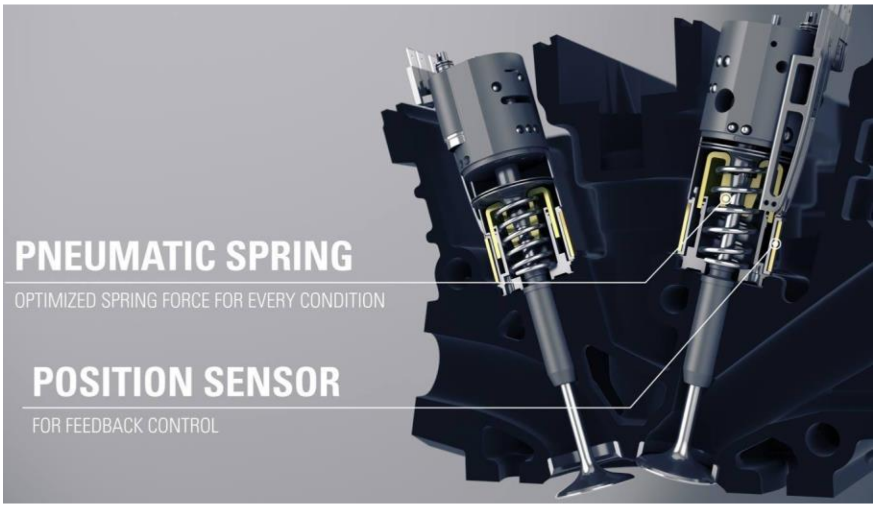

Figure 9. FreeValve technology [22]

Another CDA method, approached by A. Gritsenko [23], involves only deactivating the injection and ignition. The tests consisted of operating with a single active cylinder, with the throttle valve fully open, the results indicating a benefit in reducing fuel consumption. This method has not been studied on a multi-cylinder engine.

2.2. Side effects of Cylinder DeActivation technology

CDA also has side effects that are worth considering. Bewsher et al. [24] presented the effects of CDA on the tribological performance of piston ring-cylinder liner, the results indicating a 9.53% increase in friction losses in CDA mode due to the decrease in oil film thickness in active cylinders due to the temperature increase in them. The results of this paper show that although the tribological consequences of CDA must be considered, they are small compared to the advantages of increased efficiency. An increase in friction losses also occurs at the connecting rod bearings [25] for cylinders that remain active during CDA, being similarly affected by the increase in temperature. N. Morris et al. presented and quantified these losses [26], in Fig. 12, observing a total increase, attributed to the friction losses at the compression ring and connecting rod bearings, of 0.5% of the burned fuel mass, reaching 1.65% and 2.61%, respectively, when using CDA.

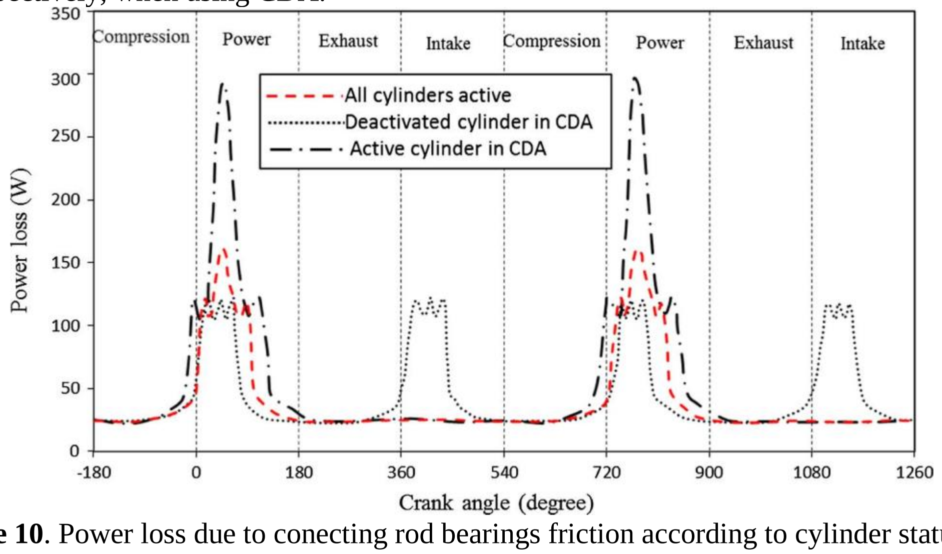

Figure 10. Power loss due to conecting rod bearings friction according to cylinder status [25]

Engine heat transfer is a side effect that varies depending on the engine configuration. In a 4-cylinder engine, for example, where the deactivated cylinders 2 and 3 are centrally located, heat transfer is not a problem, both for the active cylinders, which will have a thermal increase in the coolant around them, and for those where the lack of combustion means a local drop in temperatures. In contrast, in a 3-cylinder engine, the heat transfer of the engine, explored by A. Bech [27], although not a problem in terms of the overall coolant temperature, it is recommended that the deactivated cylinder should be the one that is located farthest from the coolant inlet of the engine, as shown in Fig. 12. Thus, the deactivated cylinder remains heated by the coolant around the active cylinders, and at the same time the temperature differences between the cylinders are reduced.

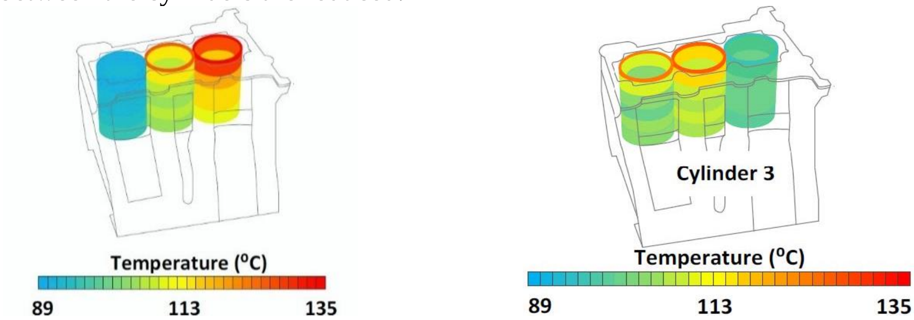

Figure 11. Cylinder wall temperatures, in case of deactivation of cylinder 1 (left) and in case of deactivation of cylinder 3 (right), in the context of the coolant inlet on the side of cylinder 1 [27]

The reduction in fuel consumption, due to the application of CDA, decreases during engine warm-up, due to the increase in the fuel used to compensate for friction losses. Engine heating is also a problem for catalyst activation, which leads to the resolution to not activate CDA until the oil has reached the optimum operating temperature [12].

2.3. Other studies

Tests performed by N. A. Abas et al. [28] regarding the emissions resulting from the application of CDA on a 1.3l DOHC engine with VVT, confirmed according to the results in Table 1, that under the same speed and loading conditions, CO2 emissions decrease, following the increase of combustion efficiency. At the same time, the HC emissions were lower due to the higher pressure in the cylinder.

Table 1. Emissions during deactivation of cylinders 2 and 3 on a 4-cylinder SI engine [28]

Mode	RPM	CO_2 [%]		HC [ppm]		λ	
		Max	Avg	Max	Avg	Max	Avg
Standard	Idling	4.59	4.54	789	765	0.79	0.78
	1000	4.60	4.37	836	801	0.90	0.89
	2000	5.90	5.60	1286	1272	0.93	0.92
CDA2	Idling	4.70	4.28	723	713	0.81	0.80
	1000	4.86	4.70	748	733	0.91	0.91
	2000	5.80	5.20	1278	1210	0.93	0.92

In the same tests, the reduction of fuel consumption in CDA mode was quantified, at the same speeds and loads, up to a speed of 4000 rpm, above this, the consumption starting to exceed that obtained with all active cylinders, as shown by the results in Table 2.

Table 2. Fuel consumption in normal mode and with 2 deactivated cylinders

Engine speed [RPM]	STD Mode		CDA2 Mode	
	Fuel consumption [Liter/hour]	Throttle open angle [°]	Fuel consumption liter/hour	Throttle open angle [°]
750	0.51	9.41	N/A	N/A
1000	0.52	10.2	0.57	11.76
1500	0.57	10.98	0.75	12.94
2000	0.77	12.16	0.91	14.51
2500	0.9	12.94	1.33	15.29
3000	1.45	13.73	1.67	16.86
3500	1.91	15.29	2.03	18.43
4000	2.48	15.8	2.55	19.22
4500	3.06	16.47	3.27	20.39

3. Conclusions

Variable displacement technologies are one of the most significant fuel saving and emissions (especially greenhouse gases) reduction methods to be applied to the spark ignition engine.

Cylinder deactivation systems offer real driving optimization of emissions performance, without requiring major engine components or systems modification, being able to be implemented and applied to existing engines and merged with other fuel and exhaust gases improvement systems.

Manufacturers are constantly trying to optimize the complexity, costs, and performance of cylinder deactivation technologies to the existing and future spark ignition engines.

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