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Abstract

The aggravated future legislation will require significantly reduced fleet average fuel consumption in combination with a nearly pollutant free operation under more or less all operating conditions, thus dramatically increasing the need for sustainable technology leap with ICE´s (Internal Combustion Engines). Especially with Gasoline engines, after the progressive series launches of "Rightsizing" and "Miller / Atkinson" – concepts, geometrically Variable Compression Ratio (VCR) is the next logical development step. However, significant progress with new, both purely technical as well as economic competitors (like 48 V) result in an intensified technology competition. In particular, the question to switch either on a broad basis and high investments in production tooling towards new engine technologies or to focus on electrification combined with only evolutionary development of the ICE, will also have an essential impact on the theme VCR.

If we restrict ourselves to pure ICE technologies, the continuous VCR systems not only offer the highest consumption and BMEP potential (e.g. Multi-Link systems), but also the most mature development status and will probably be the first VCR systems to be implemented in series production. As the market development of electrification and the cross-impact on the ICE technologies are currently difficult to quantify, the concentrating on a dedicated single technology results in high utilization risk for production facilities. Thus it must be expected, that in the near future the focus will be shifted towards modular

technology approaches that allow a flexible response to changing market requirements.

In this context, 2-step VCR systems, water injection and enhanced turbocharging like SC (Series Compressor) turbo as well as an advanced process control (SPCI - SPlit Compression Intercooled), provide a higher modularity and better integration capability into existing engine families, but also offer lower fuel consumption and BMEP potential than fully variable VCR systems.

With the 2-stage VCR systems, AVL opens new ways with an oil pressure actuated Telescope Conrod which requires to master problems which are unsolved up to now, but will set new standards in terms of modularity, cost and ease of integration in existing engine families.

With Gasoline engines, "Miller / Atkinson" - concepts are currently the most cost-effective fuel economy concepts and will develop towards a dominating mainstream technology. The next step to improve performance and BMEP range of such systems, preferably at the charging system itself, in which case a two-stage compression with intercooling is the key point. The thus significantly improved charging efficiency allows either to extend the hitherto limited BMEP and performance range of conventional "Miller approaches", or to utilize the more effective charging to relocate a higher share of the compression from the cylinder towards the charger (SPCI) and to exploit the exhaust energy in a cost effective way.

While such new approaches intensify the competition of ICE technologies, they also allow adapting the ICE in a modular design more efficiently to the requirement profiles which will be in future more differentiated.

Introduction

Analyzing the legislation scenario for 2025+, it becomes obvious that complying simultaneously both with significantly reduced fleet-CO_2 resp. CAFE (Corporate Average Fuel Economy) standards and dramatically enhanced limits for pollutant emissions (e.g. RDE (Real Driving **E**missions), China 6b,…) cannot be managed just with conventional, ICE based powertrains. However, the approach, to do that primarily by increasing the share of electrified powertrains and less by a focused refinement of ICE base powertrains, has already proven in the past to be quite risky due to insufficient market acceptance of EV´s.

The quite comprehensive consequences of the “Dieselgate” have brought new, often emotionally and politically biased facets to the competition between conventional and electrified propulsion systems

The far-reaching consequences of the "Diesel Gate" have now brought new, often highly emotional and politically influenced facets in competition between conventional and electric propulsion systems. There is an expectation that in the period 2025 plus / minus, battery electric vehicles will become cost competitive to conventional powertrains. This initiates the question of to what extent it should be invested in a next, costly and capital-intensive technology leap for the ICE, or the focus should be set on electrification with a just gradual development of the ICE. Especially the series introduction of variable compression ratio, which represents the next logical step in the further development of the gasoline engine in particular, is the focus of considerable debates.

Status Quo

The subject variable geometric compression ratio (hereinafter abbreviated with VCR…Variable Compression Ratio) is for decades considered as an essential step in ICE technology - comparable to the transition from the naturally aspirated engines to charged ones or from indirect to direct injection. In contrast to these two technologies, which have become established with both Diesel and Gasoline engines as indispensable "mainstream" technologies, the VCR item is to be considered much more complex. The statement: "VCR is the holy grail of engine design" (Cristian Chapelle, PSA, SIA Paris 2015) describes the VCR status in very subtle ways. A "miraculous vessel that grants felicitousness and eternal youth " (Wikipedia) correlates well with the attitude of the technical expectations; the continuing search for the Holy Grail is to convert parallels in the decades of trying to develop an inexpensive VCR series solution for the mass market.

The determination of the geometric compression ratio for decades has been the "classic" trade-off in the development of conventional combustion engines. Both with the Diesel engine, but in particular with the quantity controlled Gasoline engine, the geometric compression always is set as a compromise between partial and full-load requirements. The demand for the highest possible geometric compression to improve high part-load efficiency is opposed by knock (Gasoline engine) or peak pressure limitations with the Diesel engine. The increasingly advanced BMEP and power ranges enhanced the compromises to be taken with deciding a fixed compression ratio. With Gasoline engines, a quite clear correlation between the maximum BMEP and geometric compression ratio is evident even with a simple statistical observation of actual production engines Fig.1.

Here, the dominant trend towards downsizing in the recent years has even enhanced this trade-off. Compared to naturally aspirated engines, the higher specific power and BMEP levels of turbocharged engines require a lowered compression ratio at full load, while the demand for high compression ratio at part load is increasingly exacerbated by the fuel consumption requirements. Looking at the distribution of the specific power versus engine displacement, high performance is no longer restricted to multi cylinder sport cars, Fig. 2.

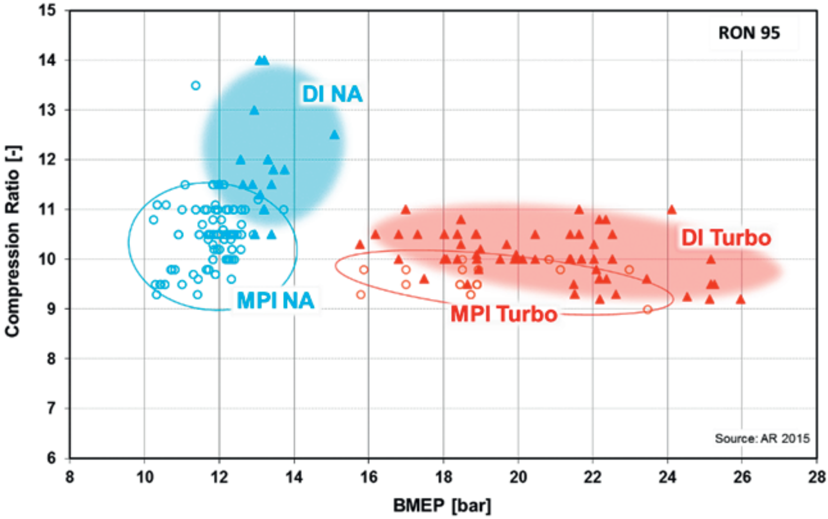

Fig. 1: Relationship between maximum BMEP and geometric compression ratio, series petrol engines MY 2015/16

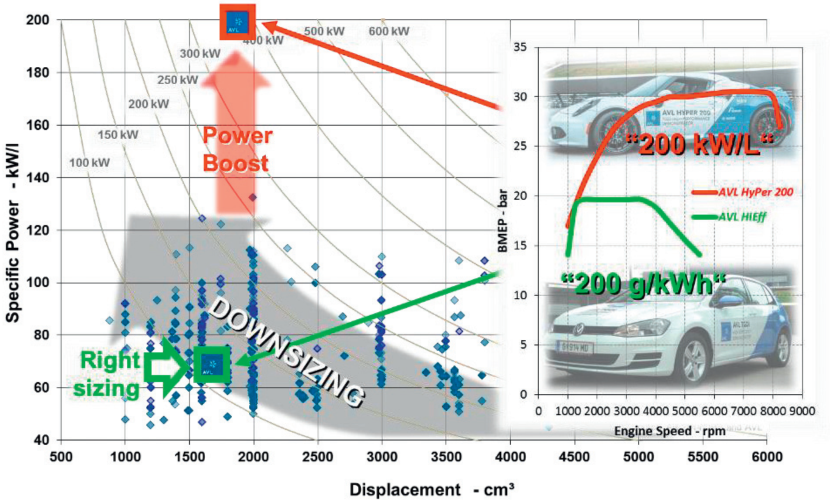

Fig. 2: Specific power of Gasoline-series engines and development trends

Compared to an initially rather homogeneous trend towards heavy downsizing arises now a pronounced differentiation. Although extreme downsizing brings significant fuel savings, especially in the low-loaded NEDC test, but also has limitations with customer real world fuel consumption and engine dynamic behavior. The consequent trend towards "Rightsizing" is reinforced by the RDE-emission problem [1] again. On the other hand, the often taken decision for reduced cylinder numbers and displacements leads to a progressive development of specific power in particular with the 4-cylinder engines. For both extremes, the AVL demo vehicles AVL *HiEff* and AVL *HyPer200* [2] may be regarded as current vertices.

Design of systems for variable geometric compression

A purely performance-oriented view describes the VCR subject only insufficiently. The actual technology drivers are not only the more stringent CO_2 requirements combined with distinct pollutant reductions and RDE as well as displacement-based tax brackets, but also result from the increasing use of variable valve trains. In particular, the implementation of the Miller or Atkinson-cycle results in a further essential criterion for determining the geometric compression ratio. Comparing engine maps each with respective optimum geometrical compression ratio for engines with fixed or fully variable valve lift respectively, Fig. 3, the implementation of a variable valve lift for Miller cycle shifts the optimal compression ratio at part load towards significantly larger values.

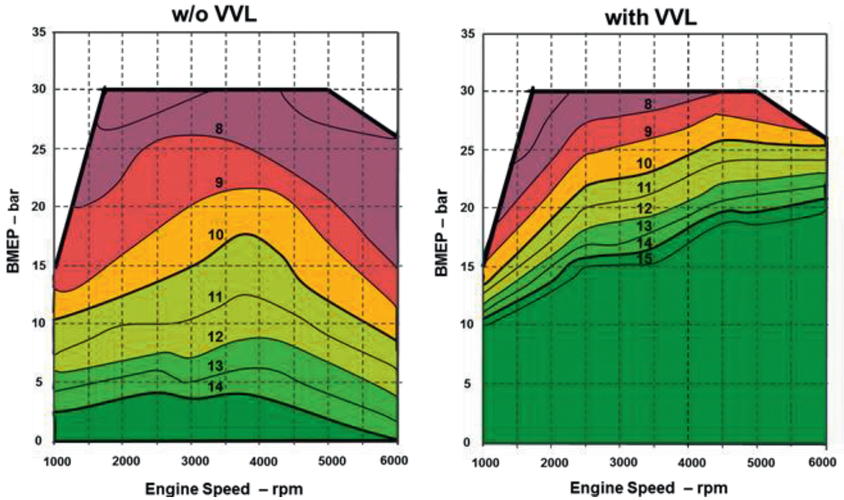

Fig. 3: Ideal geometric compression ratio with turbocharged GDI engines with and without variable valve lift

An idealized, purely theoretical approach would predict for a variable valve lift in the lowest load range even up to geometric compression ratios of 20 BSCF benefits. In practice, however, depending on the stroke / bore ratio, geometric compression ratios of larger 14 can be implemented only with limitations. The unfavorable combustion chamber geometries required for high CR, result then already in disadvantages in the combustion process, often more than offsetting the theoretical benefits of higher CR. In addition, the required tolerance-chains and the over proportional influence of combustion chamber deposits with geometric compressions CR > 16 must be considered as critical for global series solutions.

Fig. 4 shows the dependency of optimal geometric compression on the valve lift based on an experimentally validated engine model for a 2.0 liter 4-cylinder GDI engine with conventional wastegate turbocharger.

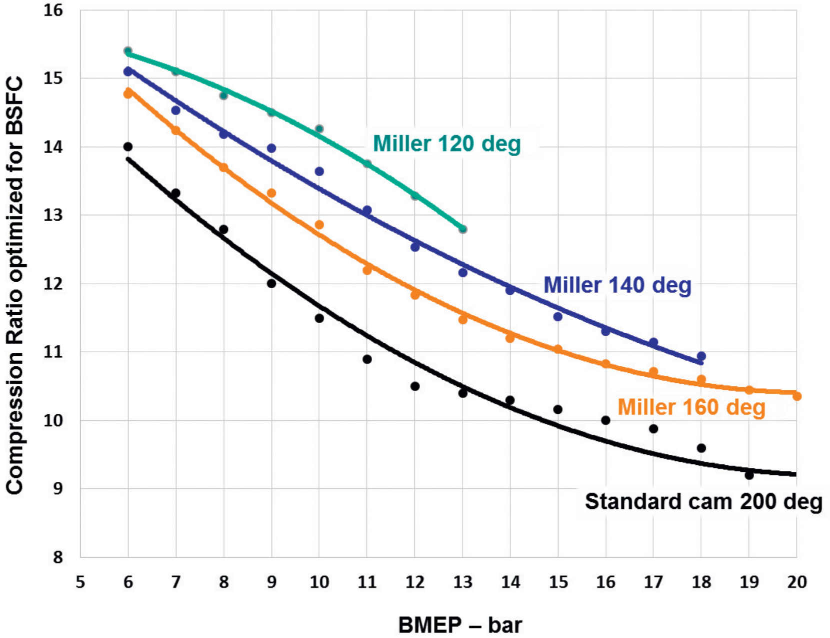

Fig. 4: BSFC-optimal geometric compression ratio depending on the valve opening period at camshaft position optimized for best fuel efficiency

The valve opening durations given in Fig. 4 are based on 1 mm valve lift respectively. In particular, short valve opening durations require in connection with an early intake valve closing ("strong Miller cycle") a corresponding adjustment of the combustion system. The early closing of the intake valves (opening duration <120° at 1 mm valve) required for the implementation of geometric compression ratios larger than 14, reduces the intake generated charge motion already to such a high extent, that BSFC increases. Thus, the interactive optimization between valve lift function and geometric compression ratio is the central theme for the layout of VCR systems.

The geometric compression takes in many ways an essential influence on the combustion:

- directly coupled by the compression pressure and temperature, as well as the turbulence generation associated with the piston position, Fig. 5
- indirectly coupled by the definition of the respective optimum intake valve closing event and the corresponding impact on the charge motion.

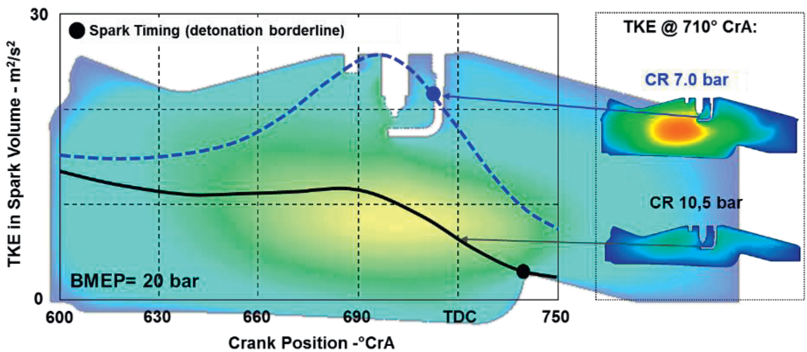

Fig. 5: Influence of the geometric compression ratio on the generation of turbulent kinetic energy in the spark region, turbocharged GDI engine

Basically, a lower geometric compression favors a later dissipation of the large-scale charge motion into turbulence, having a positive effect at high BMEP and the respective late ignition timings. Nevertheless, with variable compression, the definition of a combustion system optimized for the whole map is a much more complex task than with standard engines. The combination of VCR with Miller cycle even multiplies the required effort.

Considering here the most demanding application, the combination of a fully variable VCR system with fully variable valve lift control, it seems unlikely that with only one fixed combustion chamber and intake geometry, the variation range of geometric compression and valve-positions can be covered in an optimal way. Rather, the question arises as to what extent the potential of fully variable systems can be utilized with the combination two-step VCR and two-step variable valve lift systems at lower development, calibration and component efforts.

As pragmatic and best manageable solution here appears to switch between two fixed configurations:

• High compression (CR > 12) with "Miller"–valve lift curves

• Standard compression ratio with full valve lift curves.

Comprehensive engine tests with fully variable VCR systems and corresponding simulations for different vehicles and driving cycles lead to the conclusion, that the realizable fuel consumption improvements are determined less by the decision continuous or 2-step VCR system, than more by the optimum definition of the compression ratio spread.

While with fully variable systems, for each application the optimal compression ratio and valve lift combinations may be optimized late during the calibration, with stepped systems, these parameters must be determined early by the hardware definition. This requires an optimal design of stepped systems considering all potential engine / transmission/ vehicle configurations already in the layout phase. Since with stepped systems the switchover causes losses are (e.g. , hysteresis), an optimum trade-off between the minimum number of switching operations and optimum utilization of the area optimum setting parameters is a highly sophisticated optimization problem for determining the compression ratio spreading.

AVL-Approach for 2-step variable geometric compression

In addition to the above considerations, a simple, modular integration into existing engine families was the most important decision criteria for AVL, to select a two-stage telescopic conrod as preferred VCR solution, Fig. 6.

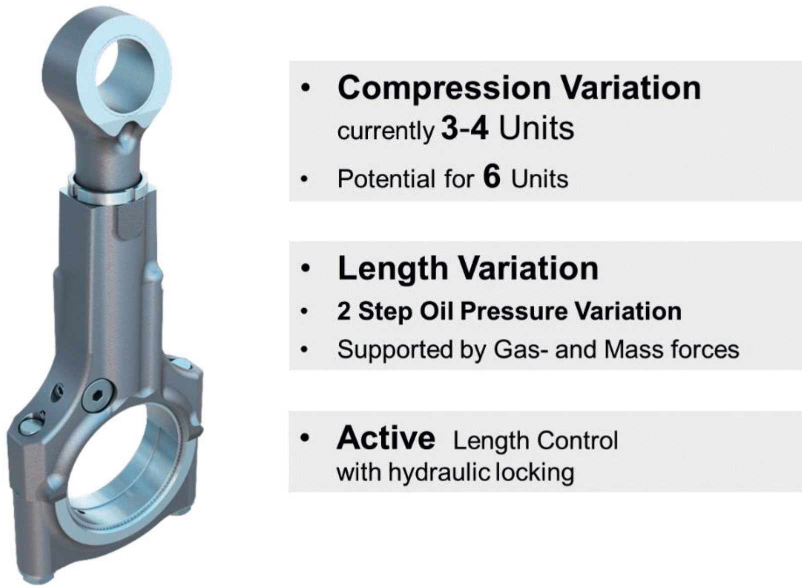

Fig. 6: 2-stage telescopic conrod for variable geometric compression

The key points of the specifications for the AVL VCR approach were:

- 2 stage compression variation with an adjustment range of up to 6 CR units
- Easy integration into existing engine designs to enable a modular engine concepts with and without VCR
- Minimal impact on the engine package, bore, stroke, bore spacing, block height and engine weight
- Concentration of the additional masses close to the large conrod eye primarily in the area of the rotating masses and thus reduced influence on the oscillating masses
- Minimized friction impact

- Contactless switching actuation based on oil pressure modulation as preferred solution, additional alternative solutions

The actual actuation of the telescope is done by using gas or mass forces. By two different oil pressure levels, the telescope is fixed in the respective mechanical end positions, Fig. 7.

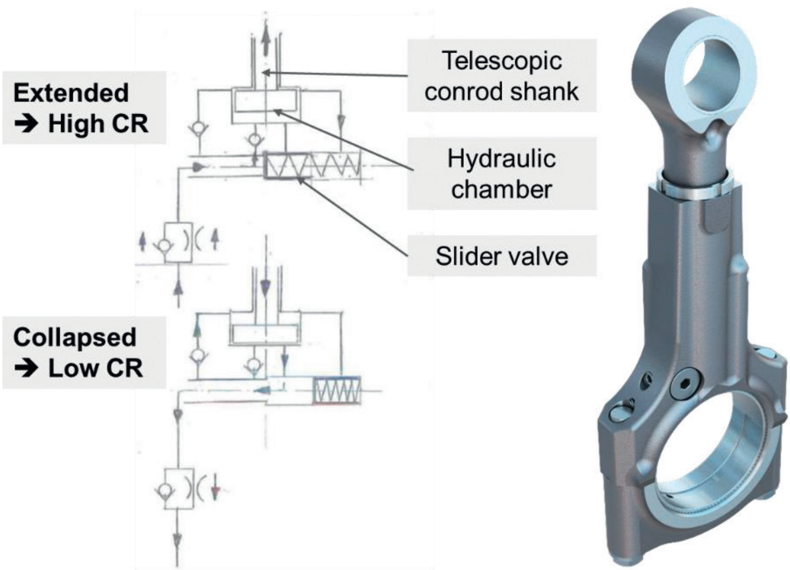

Fig. 7: VCR actuation: fixing the telescope in the end positions by modulating the oil pressure (schematic diagram)

The hydraulic operation, Fig. 8, provides the most attractive solution regarding both function, manufacturing aspects and cost, but also has the highest development complexity and is often assessed to be technically not feasible.

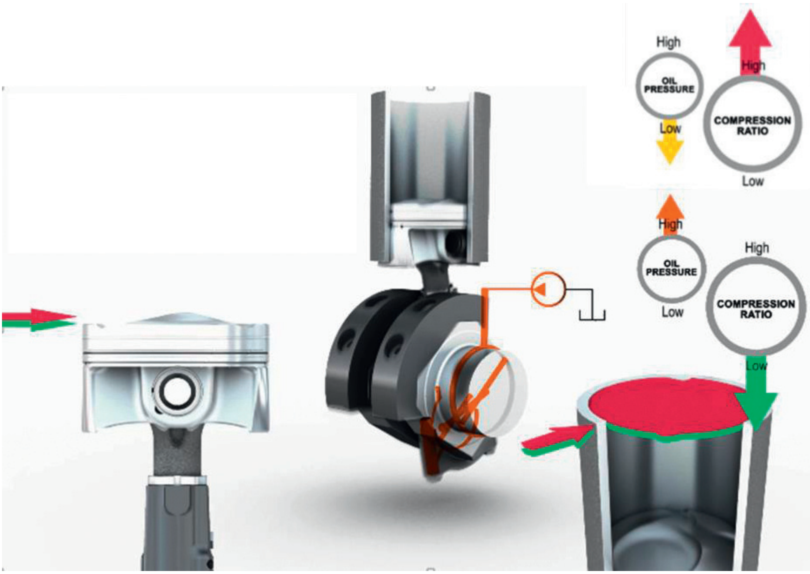

Figure 8: AVL VCR: Operating principle of hydraulic actuation

AVL is here on a quite good way to confirm the functional maturity already proven on a single cylinder engine, Fig. 9, also at the multicylinder engine.

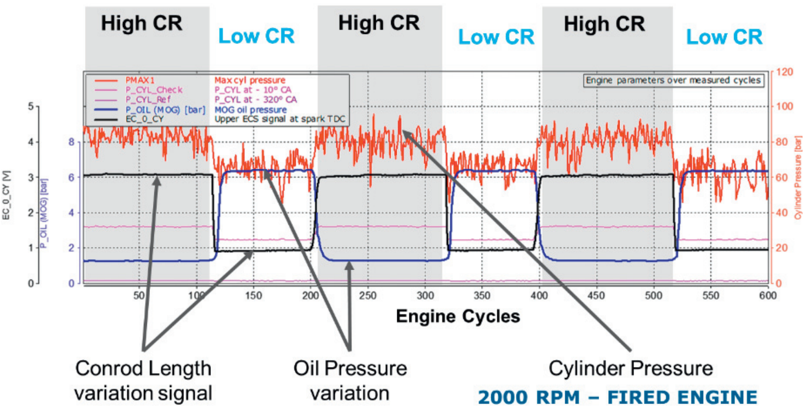

Fig. 9: VCR actuation at the fired single cylinder engine

Technical competitors to geometrically variable compression ratio

The actual basic task for VCR is to reduce pressure and temperature at high engine loads to such an extent that neither knocking nor irregular combustion results in disadvantages or additional risks, even based on a high geometric base compression ratio optimized for part load. Fig. 10 shows an overview of the most important individual measures for lowering compression pressure and temperature in turbocharged engines.

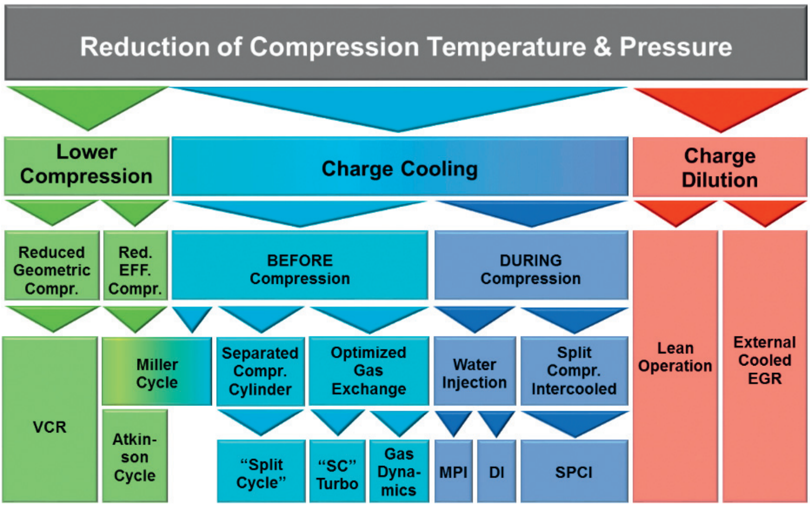

Fig. 10: Measures to reduce compression end temperature and pressure

Miller / Atkinson Cycle

The main objective of gas exchange layouts with extremely early intake closing (Miller cycle) or late intake closing (Atkinson) basically is less a reduction of the effective compression, but a simple realization of an extended expansion ratio. However, a prerequisite for the implementation of fuel economy benefits is a sufficiently high geometric compression ratio, Fig 11.

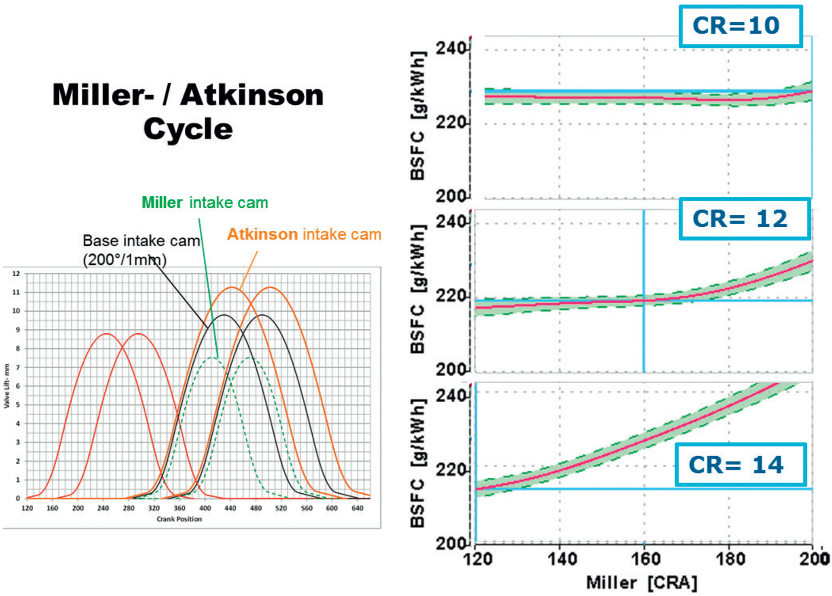

Fig. 11: Influence of the geometric compression ratio on the high-load BSFC potential of early intake valve closing (Miller cycle)

Purely theoretically, the ability to reduce the effective compression by valve timing actually might be considered as a competitor for geometrically variable compression. However, since is only feasible at a reduced cylinder charge, even in combination with a variable intake valve closing (phase shifter) the functionality of a variable effective compression is not possible in a physically reasonable sense. Thus, especially the combination of Miller cycle with variable valve lift will become in future an additional driver for measures to reduce compression temperature and pressure. In contrast to the Atkinson cycle, in which the push back of charge into the manifold will result in increased charge temperature in the intake passage, with the Miller cycle, the expansion after the early intake valve closing results in lowering the charge temperature. When designing the mixture formation, re-condensation of vaporized fuel during this expansion has to be considered especially with cold engine.

With an appropriate system layout, the early intake valve closing also enables not to waste excess boost pressure by opening the waste gate, but to use it as a positive gas exchange work and thus providing the easiest way of exhaust energy recovery. The early intake valve closing, however, also has significantly adverse effects on the charge motion and requires a sophisticated optimization of the combustion system. In a well-tuned variant, the Miller cycle is the by far the most cost-effective approach for fuel consumption improvement of Turbo engines [2,3], but is limited in terms of full load potential both by the high geometric compression and the low intake valve lift.

Water Injection

By the first series introduction of a high-performance application [4] the in principle well-known water injection has gained new momentum. In addition, since vehicle platforms will offer a corresponding tank volume for the SCR exhaust aftertreatment of Diesel variants to be also used as water tank, the entry threshold for series launches of water injection has improved. Thus the water injection can be applied not only to improve performance and avoid full load enrichment, but also to reduce BSCF in the stoichiometric high load range Fig. 12.

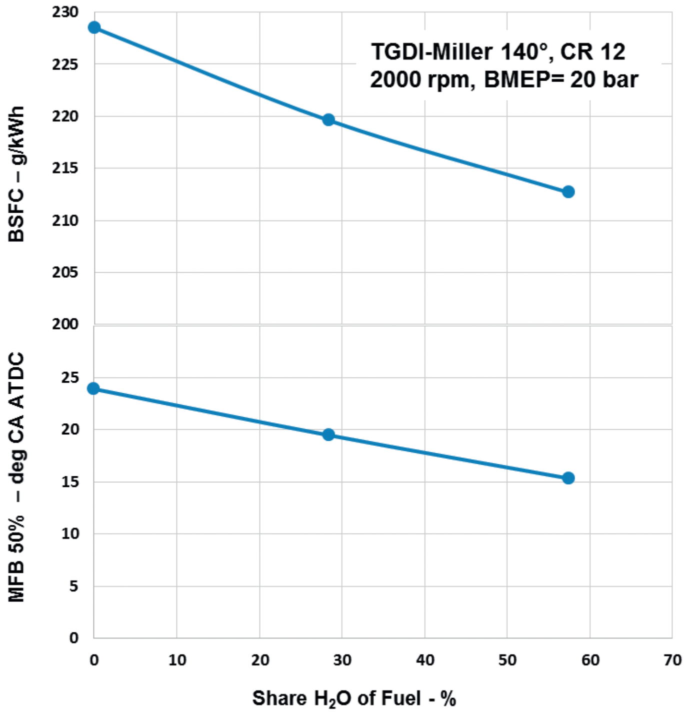

Fig. 12: Influence of water injection (MPI) on high-load BSFC

The significant reduction of the charge temperature and thus reduced knock tendency enables a favorable knock limited combustion position and corresponding fuel consumption advantages. At least with an MPI version of the water injection, the safe provision of adequate amounts of water is the main challenge.

Charge Dilution

Water vapor, relevant as an additional as knock inhibitor, is also available with cooled EGR. However, in contrast to the water injection, the temperature reduction of the charge is restricted on the one hand by the absence of heat of evaporation but also by the limited re-cooling of the exhaust gas (to avoid condensation). Other limitations arise from the significantly higher required compressor capacity. However, cooled exhaust gas recirculation is not only applied to reduce the enrichment requirement at full load, but also serves to improve BSFC consumption in the load range > 5 bar BMEP.

Refined compression process

The limited intake generated charge motion level restricted by the early intake closing of the Miller cycle combined with the high geometric compression ratio is a significant challenge for the knock behavior of turbocharged engines. Under such conditions, turbo engines respond very quickly with a strong "downward spiral", Fig. 13.

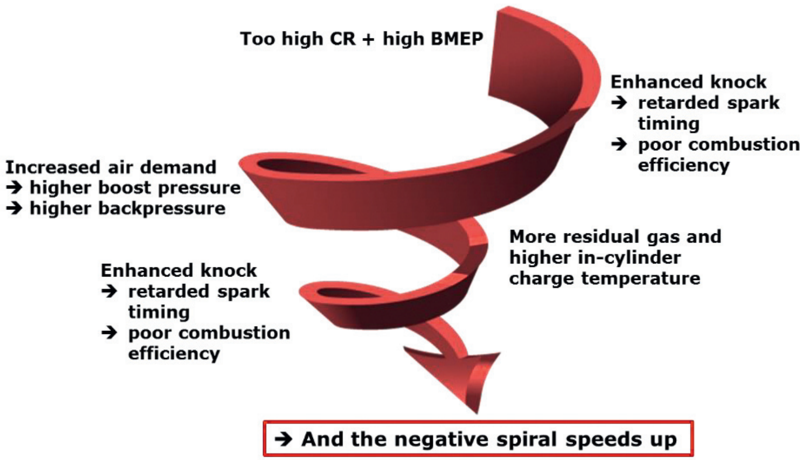

Fig 13: Negative "Turbo spiral"

This unfavorable knock behavior results in a very late combustion position and consequently poor efficiency, high exhaust temperature and additional enrichment requirements. The resulting higher air demand requires increased boost pressure and consequently also higher exhaust backpressure at higher residual gas content with the corresponding negative impact on knocking behavior and the resulting consequences.

Often comparatively small differences in the initial conditions can reverse the direction of the "Turbo spiral". Based on an already refined combustion system, a focused optimization of these problem areas sensibly starts at the turbocharger itself with the aim to generate the required boost pressure with reduced exhaust backpressure. In this case, the transition from one stage to a two-stage compression with interstage cooling proves as an effective means to reduce the required compressor power, Fig. 14.

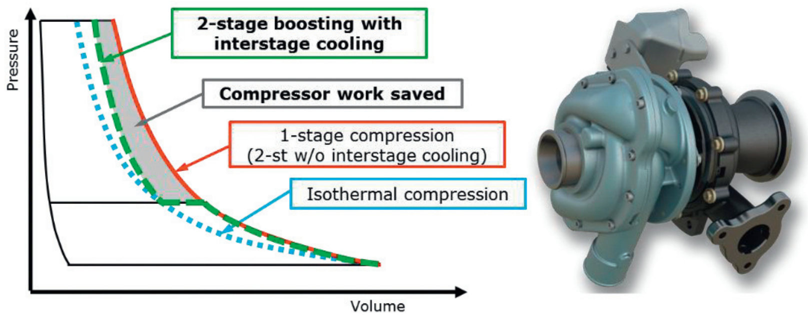

Fig.14: Two-stage compressor with interstage cooling in combination with a single-stage turbine - Honeywell SC-Turbocharger (SC..Series Compressor)

The combination of a two-stage compressor with only one single-stage turbine avoids the disadvantages of a two-stage turbine especially critical with Gasoline engines. Besides the advantage of wider compressor maps, the higher compressor efficiency turns the "Turbo spiral" in a positive direction, Fig. 15.

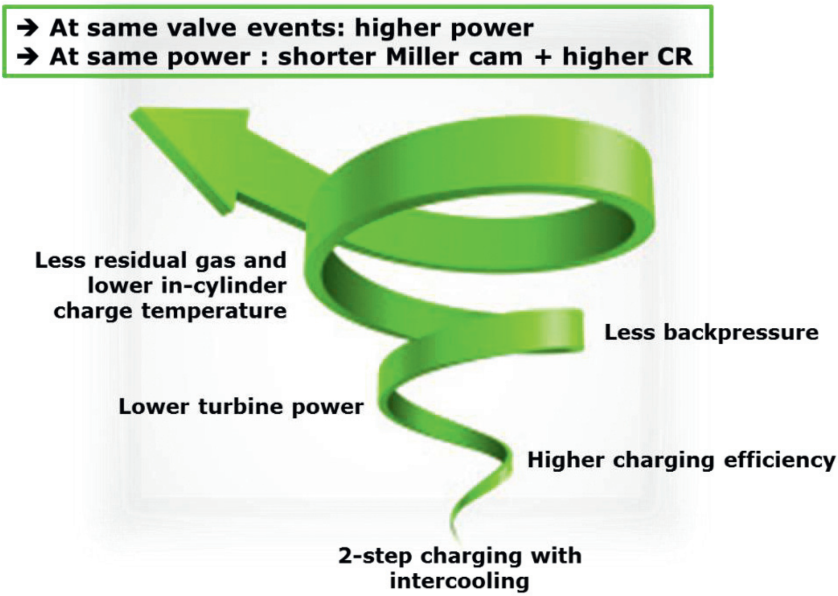

Fig. 15: Positive „Turbo spiral“

Thus the "Turbo spiral", illustrated already in Fig.13, will run in the reverse direction.

The lower compression temperatures can be implemented in different ways. With unchanged layout of the (Miller) valve events, the charge pressure and thus both the BMEP as well as power can be raised. Fig. 16 shows the comparison of a conventional single-stage wastegate turbocharger with an SC-charger and intercooling.

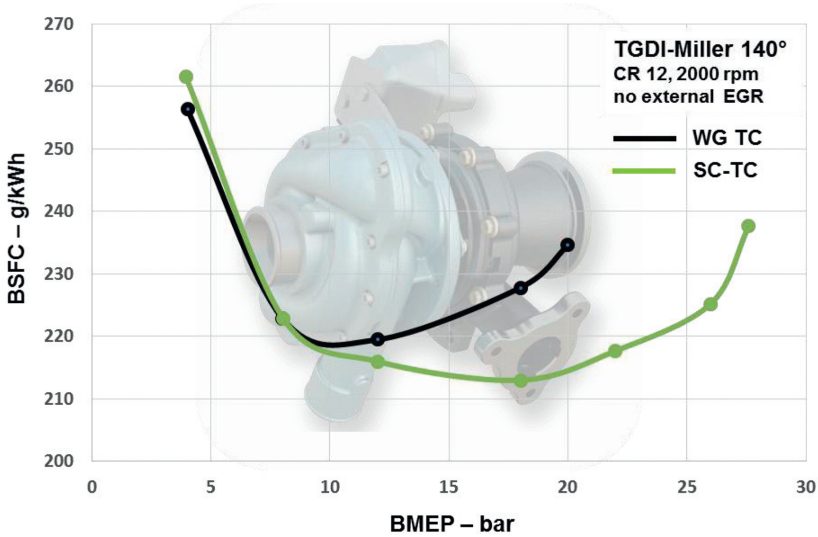

Fig. 16: Comparison of different charging systems, load sweep at 2000 rpm (simulation)

Based on simulations, it can be expected that the performance potential of a typical Miller layout (140 ° cam length at 1 mm valve lift, CR 12) of approximately 75 kW / l can be extended at least with enrichment above 90 kW / l. However, this has to be confirmed as well as the stoichiometric performance potential at the multicylinder engine.

The alternative possibility is to implement the higher charging pressure potential at the same power in a more extreme designed Miller cycle with higher compression ratio. The objective is not so much a further extended expansion but actually to organize the main compression in two stages with intercooling (SPCI-Split Compression Intercooled)

System Comparison

As a basis for comparison of the various technical approaches to reduce compression pressure and temperature, a 2.0L 4-cylinder TGDI engine (Miller 140 °, ε = 12) was selected. Since the results underlying the individual technologies originate from different engines, this comparison was carried out as a simulation, but correlated in best way with test results.

Fig. 17 shows the comparison of combustion chamber pressure and temperature during the induction in the load point 2000 rpm, 20 bar BMEP.

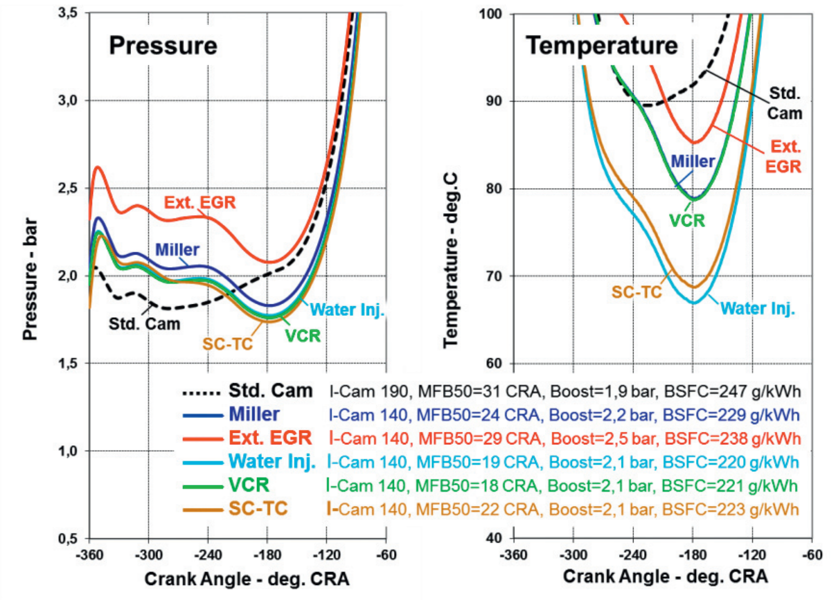

Figure 17: Comparison of combustion chamber pressure and temperature during the induction - different measures for lowering compression pressure and temperature

At 2000 rpm, 20 bar represents the maximum achievable BMEP limit level with the initial configuration (Miller-cam 140 °, CR = 12, standard wastegate turbocharger) under the given boundary conditions ($\lambda = 1$, turbine inlet temperature <980 ° C).

Applying full valve lift (190 ° opening duration) as a reference, provides the lowest boost pressure demands, but results in high combustion chamber pressure and temperature at the end of compression due to the high fresh gas charge amount, Fig 18.

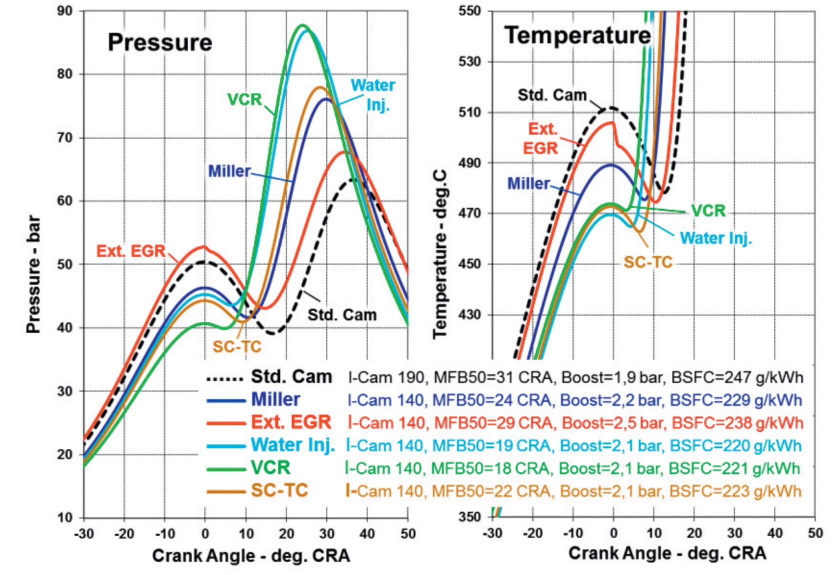

Fig.18: Comparison of combustion chamber pressure and temperature during the high pressure phase - different measures for reduction of compression pressure and temperature

Due to the resulting late combustion position under the given constraints for air ratio and turbine inlet temperature, the BMEP level of 20 bar is no longer achieved.

While with the shorter Miller timing (140°), the required boost pressure is increased by about 300 mbar compared to the full valve lift cam (190°), due to the lower exhaust gas temperature, the mixing temperature remains similar and is lowered by the expansion after the early closing by about 20 °C. This allows an earlier combustion position reducing BSFC from 247 to 229 g/kWh.

Due to the fact, that external cooled EGR needs another 300 mbar boost pressure, in this specific load point the improvement potential is limited. However, this is no way to generalize to the whole map, here partly considerable advantages through cooled exhaust gas recirculation can be found.

Even as MPI, the water injection offers a significant temperature drop resulting in an earlier combustion position reducing BSFC from 229 to 220 g / kWh.

Despite a different mechanism, finally the geometric variable compression ratio (CR 12→9) offers similar reductions of the compression end temperature and BSFC improvements as the water injection of 25% of the amount of fuel.

The 2-stage compressor with intermediate cooling is seen within one group with VCR and water injection regarding lowering the compression end temperature.

<u>Fig. 19</u> shows a simplified assessment of the different system approaches, however is not limited to the exemplified load point.

As expected, the continuously variable geometric compression shows the largest improvement potential, however, also the highest development, component and integration efforts. Two-stage VCR systems are somewhat lower in the potential for improvement, however, are much more favorable in terms of effort and easy integration. In particular, the telescope conrod is characterized by comparably high modularity. Water injection and two-stage compressor with intercooling come in individual aspects amazingly close, where said two-stage intercooled compressor is practically imperceptible for the end customer, the water injection requires willingness to refill water.

	Variable Geometric CR	Miller / Atkinson	Water Injection	Split Compression Intercooled	Charge Dilution
Reduced Compression Temperature & Pressure	++(+)	++	++	++	+
Extended Expansion Ratio	0	++	0	0	0
Impact on charge motion	-	---	-	0	--
Low end torque	++(+)	--	++	0	--
Power	+	-	+	+	--
Transient response	+	--	0	0	-
Impact on engine architecture	--(-)	0	0	-	0
Impact on heat rejection	0	0	0	--	-
Add. Fluid	0	0	---	0	0

Fig. 20: Evaluation of different measures to reduce compression pressure and temperature

Conclusions

By the stringent future legislation that requires simultaneously reduced fleet consumption and pollutant free ICE operation under virtually all operating conditions, the need for sustainable technological advance with ICE will be significantly increased. In particular, with the Gasoline engine, after the progressive series launches of "Rightsizing" and "Miller / Atkinson" – concepts, the geometrically variable compression ratio is the next logical development step. However, progress with new, both purely technical as well as economic competitors to the variable geometric compression, the technological competition will be intensified.

Especially the question to switch either on a broad base and with high investments to new ICE technologies, or to focus on electrification at only evolutionary development of the ICE, will have an essential impact on series introduction of VCR. Continuous VCR systems (e.g. multi-link systems) not only have the highest BSFC and BMEP potential, but also, compared to 2-step VCR systems, the most mature development status and will be implemented as first VCR systems in series. However, with such systems the significantly modified cranktrain results in limited modularity.

Although at least one 2-step VCR system, water injection, improved turbocharging like SC (Series Compressor) turbo and advanced process control (SPCI..Split Compression Intercooled) have a lower overall potential, they offer significantly higher modularity and better integration capability into existing engine families.

An additional cross-influence is also originating from the electrification, especially from the topic 48V systems. Although they are not representing a direct technical competitor to the ICE technologies, but very well compete in the economic sense with ICE measures - especially in the question of what mix of technologies the future fleet CO_2 values can be displayed with minimal cost.

A cost-optimal technology mix is of course determined by a variety of other parameters, such as vehicle portfolio respective production volumes and global sales profiles. Since these constraints differentiate very strongly for each OEM, it can be assumed that in the future there won´t be a uniform technology trend, but the technology diversity will be even enhanced.

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