Vienna
Motor
Symposium
2021

42nd International Vienna Motor Symposium
29-30 April 2021

2021-30

ZVG (50kWe) The Vibration Free, Emission Minimized and Sustainable Solution for an Electrified Future

ZVG (50kWe) die vibrationsfreie, emissionsminimierte und nachhaltige Lösung für eine elektrifizierte Zukunft

Dipl.-Ing. (FH) M. Graz, F. Obrist, Dipl.-Ing. P. Zanolin, Dipl.-Ing. (FH) O. Obrist,
Obrist Powertrain GmbH, Lustenau

This paper has been presented and published on the occasion of the 42nd International Vienna Motor Symposium 2021.
All papers of this symposium are published in an anthology (ISBN 978-3-9504969-0-1) and can be ordered from the Austrian Society of Automotive Engineers (https://vienna-motorsymposium.com, https://oevk.at, Email: info@oevk.at).

Abstract

The **Z**ero **V**ibration **G**enerator ZVG (50kWe) Volume Design is the consequent evolution of the existing ZVG (40kWe) with focus on cost reduction, technical improvement, and elimination of emissions. The ZVG comes with new and highly innovative technical optimizations such as a balancing system to compensate unbalances of the 1st, 2nd and higher orders, the usage of only one generator and a compensation mass to eliminate the rolling torques generated during transient operations. It can also be operated with the “green” fuel methanol for a CO_2 neutral, NOx minimized and particle free operation. Using methanol, the engine can be operated with a compression ratio above 1:20 with an additional increase of combustion efficiency. Obrist Powertrain will present the current design of the ZVG as well as the test bench results for gasoline and methanol.

Kurzfassung

Der **Z**ero **V**ibration **G**enerator ZVG (50kWe) Seriendesign stellt die konsequente Weiterentwicklung des vorhandenen ZVG (40kWe) dar, mit dem Fokus auf Reduktion der Kosten, technische Weiterentwicklung sowie die Reduktion bzw. Eliminierung der Emissionen. Der ZVG besticht durch neue hochinnovative technische Neuerungen wie das Kompensationssystem zur Eliminierung der Ungleichförmigkeiten 1ster, 2ter und höherer Ordnungen.

Die Kompensation der Rollmomente im transienten Betrieb wird trotz Verwendung von nur einem Generator mittels Kompensationsmasse auf der Kurbelwelle ermöglicht. Außerdem besteht die Möglichkeit den ZVG mit dem „grünen“ Kraftstoff Methanol zu betreiben, um so einen CO_2 neutralen, NOx minimierten und partikelfreien Betrieb sicherzustellen. Durch die Verwendung von Methanol kann der Motor mit einem Verdichtungsverhältnis von 1:20 betrieben werden was zu einer deutlichen Steigerung des thermischen Wirkungsgrades führt. Obrist Powertrain wird den aktuellen Designstand sowie Messdaten vom Motorenprüfstand für den Betrieb mit Benzin und Methanol präsentieren.

1 Development History

In 2011 Obrist Powertrain started the development of a highly efficient, highly compact, and low-cost two-cylinder engine to support electric energy for serial hybrid vehicles called HICE (Highly efficient Internal Combustion engine). One key IP of the HICE was its counter-rotating crankshafts to compensate the unbalance of first order as well as the integrated generator to generate electric power. (Figure 1 shows the HICE proof of concept with one integrated generator)

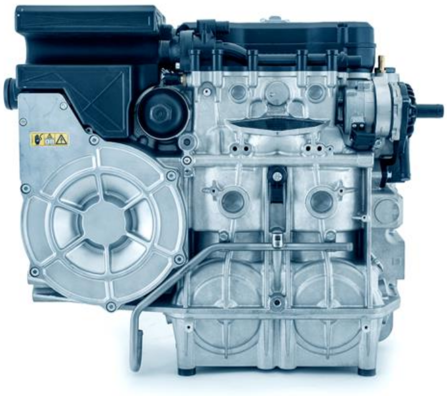


Figure 1: HICE Proof of concept with one integrated generator

Based on the results from bench test measurements and the application in demonstrator test vehicles, Obrist Powertrain transferred the HICE into the first generation of the Zero Vibration Generator. The focus was still on high efficiency and low production cost but additionally on the compensation of the remaining unbalance of second order as well as the rolling torque during transient operation (acceleration and deceleration) to enable an electric driving feeling during hybrid operation in the serial hybrid vehicle. The compensation of the unbalance of second order was realized using two counterrotating generators, operating with double crank-shaft speed and a defined unbalance on the generator shaft. This counter operation of the crankshafts and the generators additionally eliminated the rolling torque during transient ZVG operation. The application in a test vehicle and intensive test bench investigation have proven the functionality of the internal compensation system. (Figure 2 shows the ZVG A-Sample with two generators)

Figure 2: ZVG A-Sample with two integrated generators

In 2020, Obrist Powertrain and AVL in Graz further improved the existing ZVG A-Sample by transferring the A-Sample to B-Sample status with the implementation of additional technical innovations and cost reduction measurements. In the following pages we will explain the development status of the ZVG (50kWe) B-Sample engine.

2 Project Scope and Development Targets

The target of the development in cooperation with AVL in Graz was the development of a ZVG B-Sample based on the development status of the ZVG A-Sample as well as the following technical and financial inventions and targets. We have listed the main technical development innovations and the rough technical specifications for the ZVG B-Sample development:

2.1) Use of one integrated generator for packaging, weight and cost reduction and therefor the implementation of a new system to compensate the unbalance of second and (alternatively) higher orders (Patent protected technology by Obrist Powertrain)
2.2) System to compensate the rolling torque during transient ZVG operation due to the reduction down to one generator
2.3) Design of the ZVG to be used for conventional gasoline (RON95) as well as green Methanol for a CO_2 neutral and emission minimized operation
2.4) Use of an aluminum cylinder block with a clearance compensation system for the steel gears of the main drive to compensate the different elongation of the aluminum housing and the steel gears over the engine temperature operating range
2.5) Design of an acoustic insulation box with access to the main service parts of the ZVG

Alongside the new target inventions, the main technical targets for the ZVG B-Sample have been summarized in the following table. (Table 1 shows the technical specification for the ZVG B-Sample)

An additional important target of the B-Sample development was the realization of a development status to be transferred to a D-Sample status without significant design changes. Based on this technical maturity level we have defined a production cost target for the mechanical parts below 550€ per ZVG for a production volume of 250,000 units per year and an amortization period of 8 years. Not included are the costs for the electronics (Inverter, Generator and ECU) as well as the exhaust system and insulation box.

Table 1: ZVG B-Sample technical specification

ZVG Specifications				**B Sample**	
Nr	**Technology Parameters**			Target Values	Tolerance
1	**Electrical Specs**				
1.1	DC High Voltage circuit	Voltage [V]	Max	420	-
1.2		Voltage [V]	Min	240	-
1.3	Max. Continuous Power DC-Power	Power [kW]	Min	40	-
2	**Engine Basics**				
2.1	Engine Displacement	[ccm]	-	999	-
2.2	Engine Design (Cylinder)	[-]	-	2	-
2.3	Fuel Type (Engine load calculation based on Methanol as reference for e-fuel)	[-]	-	RON 95 / Methanol	-
2.4	Piston Operation	[-]	-	CW/CCW	-
2.5	Fuel Injection	[-]	-	Manifold Injection	-
2.6	Number of Injection Valves	[-]	-	2	-
2.7	ZVG Operation Control Strategy	[-]	-	λ1	-
2.8	ZVG Speed Range for Full Load	[rpm]	Max	5000	-
2.9		[rpm]	Min	1000	-
3	**Cooling**				
3.1	**"Option 1" Single Circuit**				
3.1.1	Total Cooling Mass Flow	[l/min]	Max	50	-
3.1.2	Cooling Mass Flow Inverter/Gen.	[l/min]	Max	10	-
3.1.3	Cooling Mass Flow Engine	[l/min]	Max	40	-
3.1.4	Coolant Inlet Temperature	[°C]	Max	65	-
3.1.5	Engine Thermostat Opening Temperature	[°C]	-	85	-
3.2	**"Option 2" Double Circuit**				
3.2.1	Mass Flow Circuit 1 (Engine)	[l/min]	Max	40	-
3.2.2	Mass Flow Circuit 2 (Inverter/Gen.)	[l/min]	Max	10	-
3.2.3	Inverter Coolant Inlet Temperature	[°C]	Max	60	-
3.2.4	Engine Thermostat Opening Temperature	[°C]	-	85	-
4	**Dimensions**				
4.1	ZVG Dimensions (with Generator / Inverter / ECU / Insulation / without Mounts & Connectors)	Width [mm]	Max	650	-
4.2		Height [mm]	Max	510	-
4.3		Depth [mm]	Max	275	-
4.4	or Equivalent ZVG Volume	Volume [liter]	Max	90	-
4.5	ZVG Weight (without catalytic converter / Fluids)	[kg]	Max	< 100	-

5	**Efficiency**				
5.1	Specific DC Fuel Consumption (best point value Lambda 1)	[g/kWh]	Max	< 255*1	-
5.2	Indicated Fuel Consumption "ISFC" (best point value Lambda 1 / Lambda >2)	[g/kWh]	Max	< 206 / < 199*2	-
5.3	Break Specific Fuel Consumption “BSFC” measured at the Generator Shaft (Best point value Lambda 1)	[g/kWh]	Max	< 232	-
5.4	ISFC Deviation over ZVG speed (1500-5000rpm)	[%]	Max	10	-
5.5	Inverter Best Point Efficiency (indication value only)	[%]	-	97	-
5.6	Generator Best Point Efficiency (indication point value)	[%]	-	95	-
6	**Other Specs**				
6.1	ZVG Reliability	[hours]	-	500	-
6.2	ZVG Cycle numbers for 500h reliability (Based on WLTP simulation)	[-)	Min	12.000	-
6.3	ZVG Ambient Operating Temperature Range	[°C]	Max	+ 52	-
6.4		[°C]	Min	- 30	-
6.5	Catalytic Converter System	[-]	-	3 Way Converter	-
6.6	ZVG Cooling System	[-]	-	Water / Glycol (50/50)	-
6.7	ZVG Mounting Position	[-]	-	Vertical	+/-30°
6.8	ZVG Noise tail pipe Value between 1500-2100 rpm	[dBA]	Max	72	-
7	**Emission Standards**				
7.1	B-Sample must fulfill following standard in an applied vehicle	[-]	-	Euro 6d	-

3 Functional Description of the ZVG B-Sample

The Zero Vibration Generator is two-cylinder engine with 999ccm and a 360° ignition timing. The system contains the base engine, an integrated generator and inverter to support electrical DC output power as well as the Engine Control Unit, sensors and wiring harness. The air inlet box with the filter system is also part of the ZVG and covered by an acoustic insulation box to minimize airborne noise emission. A compact exhaust system with a 3-way catalytic converter and a silencer completes the stand alone ZVG-Unit. (Figure 3 shows the outside view of the ZVG B-Sample without insulation box and exhaust system)

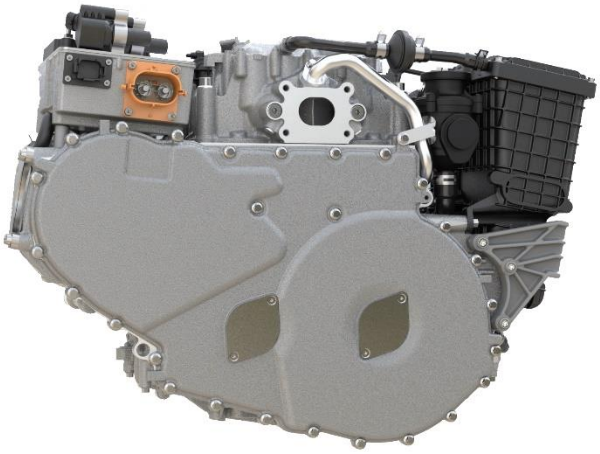


Figure 3: Outside view of the ZVG B-Sample without insulation box and exhaust system

The unique and patent protected counter-rotating operation of the crankshafts is compensating the unbalance of first order. A bottom mounted camshaft is supporting minimized complexity and engine design height. Due to the limited operating speed range of 1,500 rpm to 5,000 rpm, the engine needs only one inlet and 1 outlet valve per cylinder and with a WOT (Full Load) operation throughout the operating range. Complex and costly partial load optimizations on the valve train are no longer necessary. (Figure 4 shows the crank and cam-train system)

Figure 4: Crank- and cam-train system

The connection between generator and combustion unit is done by a gear set with an intermediate gear and a transmission ratio of 1:2 to operate the generator at double crank speed. The generator is supporting the electrical power and is used to control the speed of the ZVG within the speed range of 1,500 to 5,000 rpm. (Figure 5 shows the main gear drive with generator)

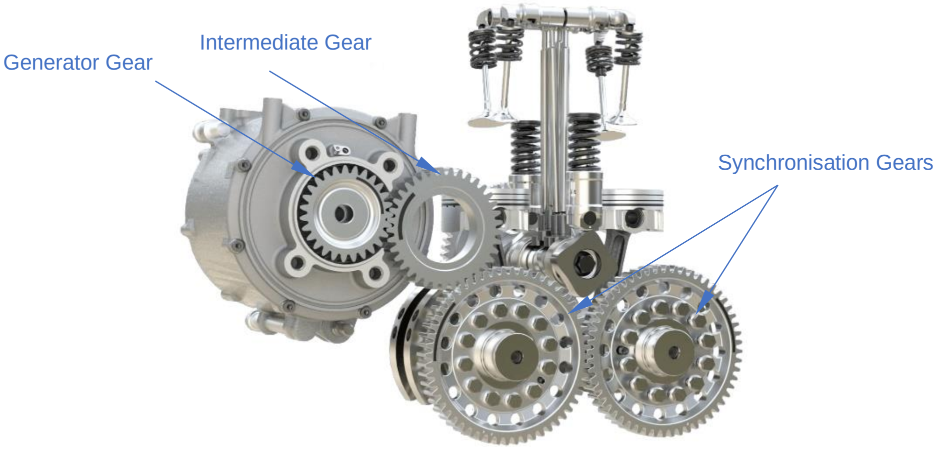


Figure 5: ZVG main gear drive with generator

The unbalance of second order is compensated by a highly innovative linear compensation system in the cam-train and the rolling torque is compensated by a flywheel on one of the crankshafts. The systems are explained in the following section 4. (Figure 6 shows the compensation system for second order and rolling torque).

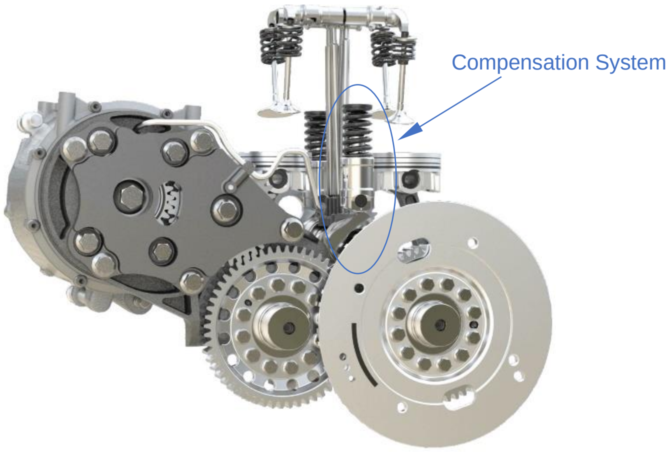


Figure 6: ZVG compensation system

To enable an operation of the ZVG in vertical and horizontal application (different engine setting) the ZVG is fitted with a dry sump lubrication system with a suction pump in the crank case and an oil pressure pump connected to the 2.8l oil tank both driven by the two crankshafts. (Figure 7 shows the pump system for the dry sump lubrication)

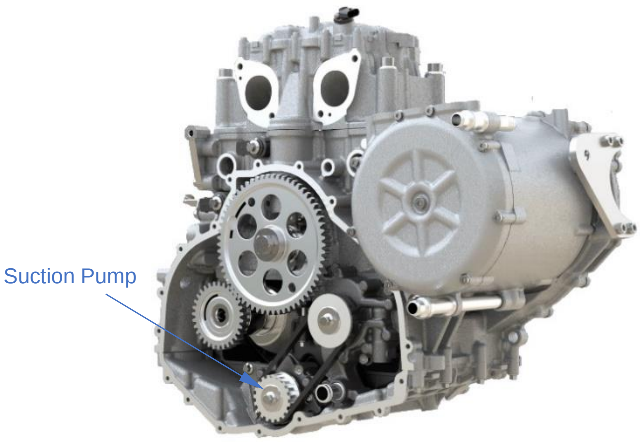


Figure 7: Oil pump system of the dry sump lubrication

The inverter is electrically and thermally connected with the generator and communicating with a CAN Bus system with the environment. The ZVG is operated with an intake manifold injection system with two injectors and operated at Lambda 1 over the whole operating range. The cooling and air intake systems complete the ZVG system. (Figure 8 shows the ZVG with Inverter, ECU, and Manifold)

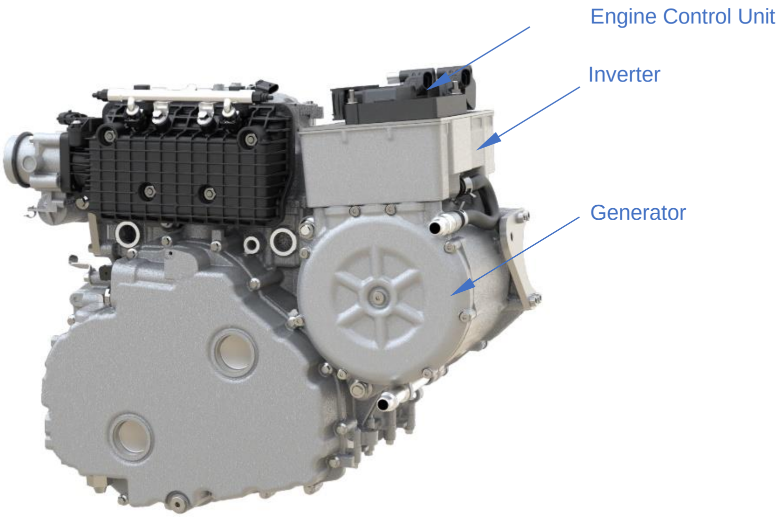


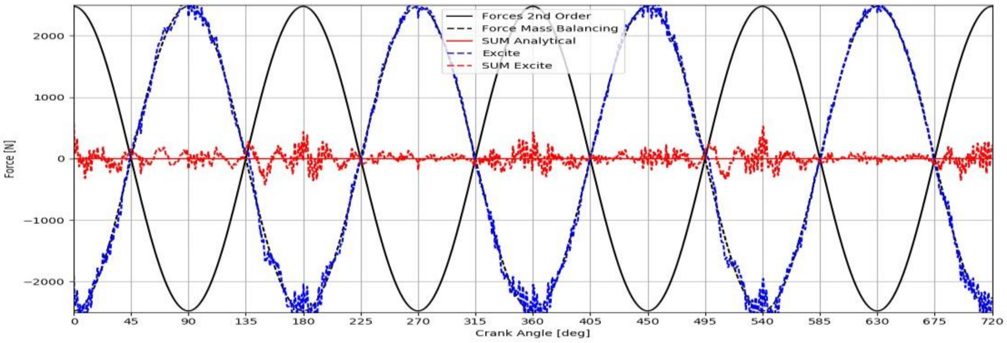
Figure 8: ZVG with Inverter, ECU, and Intake Manifold

4 Technical Highlights of the ZVG B-Sample

4.1 Use of one integrated generator for packaging, weight and cost reduction and therefor the implementation of a new compensation system to compensate the unbalance of second and (alternatively) higher orders.

The new and innovative architecture of the ZVG allows a full compensation of the unbalance of first, second and higher orders. The counter-rotating crankshafts are used for a full compensation of the unbalance of first order. For the compensation of the second order generated by the finite length of the conrods, we have implemented a new highly innovative compensation system to the valve train system by using two linear compensation masses. The counter-rotating conrods are internally compensating the horizontal parts of the unbalance of second order. Finally, we only have to compensate the vertical fraction of the unbalance of second order by the new compensation system. In comparison to state-of-the-art compensation systems which are using two double speed compensation shafts (for a fully balanced 4 cylinders in line system) with its drive system, this new compensation system shows a technically simplified and cost minimized solution. (Figure 9 shows the new compensation mechanism) The current design of the balancing cam with 4 exaltations, to compensate the two vertical excitations of the conrods with the half speed rotating cam shaft, allows a full balancing of the unbalance second order. The compensation of unbalances of higher orders can be realized by adding additional exaltations to the balancing cam shape. (shows the simulation results of the compensation system)

Figure 9: Compensation system



To ensure continuous contact between the balancing mass and the balancing cam, a spring system must be designed and implemented, as well as a lubrication optimized shape of the balancer mass to minimize the friction of the balancing system during operation. (Figure 11 shows the simulation results of the balancer contact load @ 1500 & 5500 rpm)

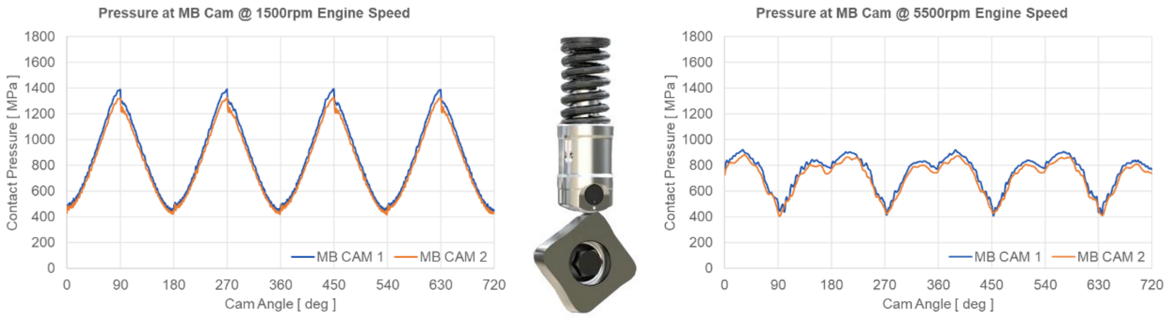


Figure 11: Balancer contact load simulation @ 1500rpm & 5500rpm

4.2 System to compensate the rolling torque during transient ZVG operation due to the reduction down to one generator

To eliminate external forces due to dynamic accelerations and decelerations of the integrated generator caused by its inertia, we have implemented a flywheel on crankshaft 1 to compensate the moment of inertia of the counter-rotation generator as well as all rotating parts inside the ZVG like camshaft, oil pumps etc. (Figure 12 shows the design and position of the flywheel system)

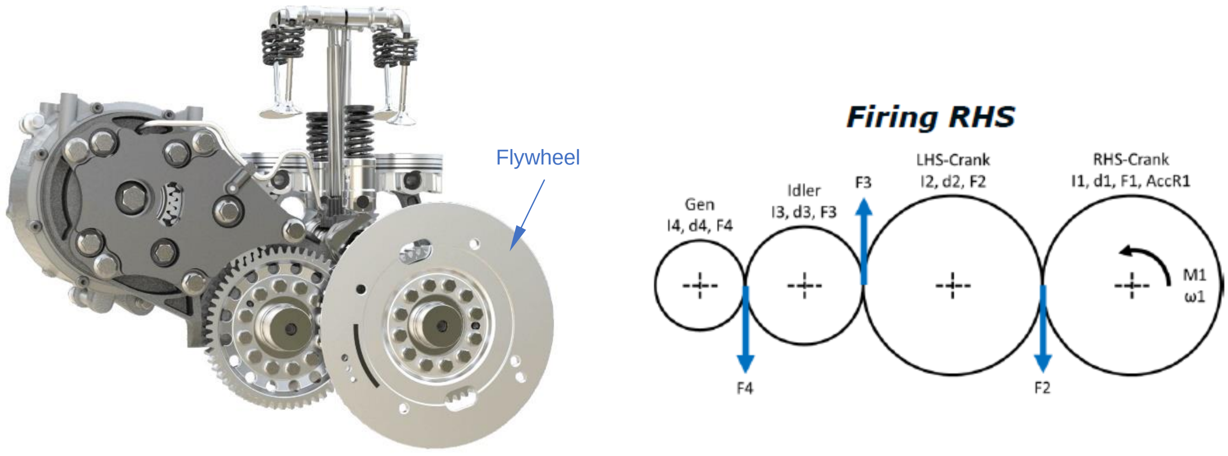


Figure 12: ZVG Flywheel system

4.3 Design of the ZVG to be used for conventional gasoline (RON95) as well as green Methanol for a CO_2 neutral and emission minimized operation

The ZVG B-Sample was designed to be operated with conventional gasoline 95 octane and with alternative “green” methanol with minimized technical adaptations on the ZVG. To fulfil this target, the mechanical and thermal load on the ZVG generated using gasoline and methanol have been investigated and simulated, and the “worst case” values have been used for the final design of the ZVG. Pre-test procedures with a 1-cylinder test engine at the AVL test bench has shown a high potential for Methanol to improve the efficiency of the ZVG by using a dramatically increased compression ratio (due to the high anti-knocking properties of Methanol) as well as dramatically reduced NOx emissions under lean burning operation. (Figure 13 shows the comparison of NOx test results for gasoline and methanol dependent over Lambda on the left side) Very interesting and promising are the values of carbon particles. Due to the molecular structure of methanol, no measurable particles are generated during combustion process independent on the Lambda value. (On the right side, Figure 13 shows the comparison of carbon particles test results for gasoline and methanol Lambda) This shows a huge potential for an operation of the ZVG without the demand for a particular filter system as well as a NOx minimized operation during lean burning operation.

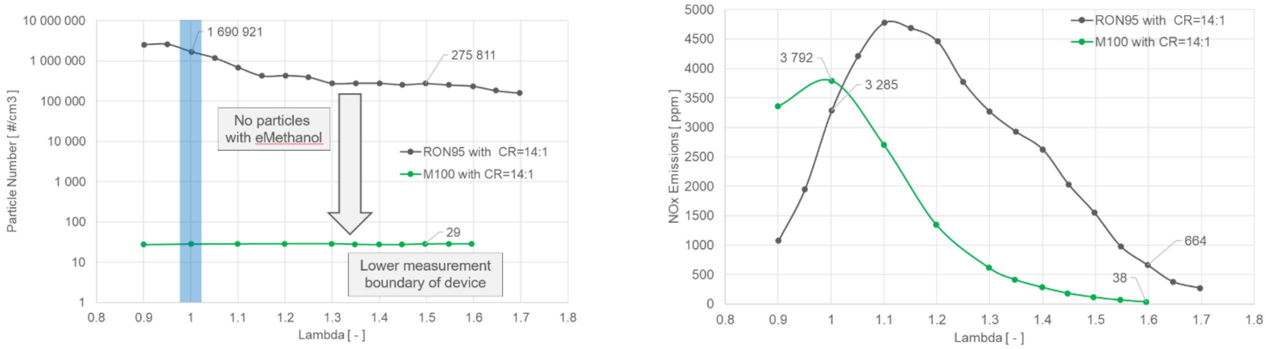


Figure 13: NOx Emission Comparison (left) and Carbon Particle Emission Comparison (right)

With the high anti-knocking properties of methanol, we have theoretically investigated the potential for the improvement of the engine efficiency based on the increased compression ratio as well as the lead burning ability of a combustion engine used in a serial hybrid system. Conventional combustion engines operated with gasoline will end with a compression ratio of 14 due to the knocking limitations of gasoline at these values. The increase of the compression ratio to 20 will lead to a theoretical efficiency improvement of 8%. (Figure 14 shows the efficiency curve of an ideal engine over compression ratio on the left side) The operation of the ZVG with lean burning can further improve the thermal efficiency of the engine by 10% as a “best case” value. During the pre-testing, an operation of the test engine up to a Lambda value of 1.6 was feasible within the CoV value of 2%. The combination of a dramatically increased compression ratio and the operation with extreme lean burning shows the potential to improve the engine efficiency by 18% in the best case with no costly or complex optimization systems. (On the right side, Figure 14 shows the efficiency potential of methanol based on compression ratio improvement and lean burning)

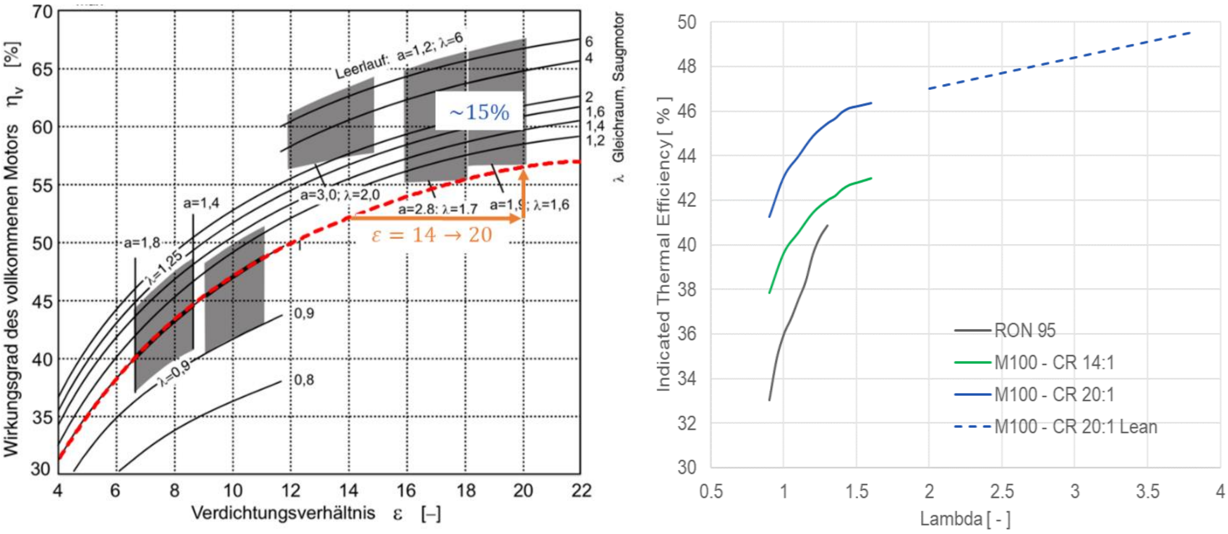


Figure 14: Efficiency curve of an ideal engine (left) and efficiency improvement potential (right)

Based on these pre-test results, AVL has investigated on two fuels for the ZVG: 95 octane gasoline and methanol. In the first step the gas forces have been determined for both fuels to identify the “worst case” scenario for the mechanical design of the ZVG. The simulation has shown a significantly higher peak firing pressure for methanol over the compression ratio. With target compression ratio value of 20:1 we are ending up with a peak firing pressure of 111 bar compared to 65 bar for gasoline with a compression ratio of 12,2:1. (Figure 15 shows the peak firing pressure of methanol and gasoline over compression ratio)

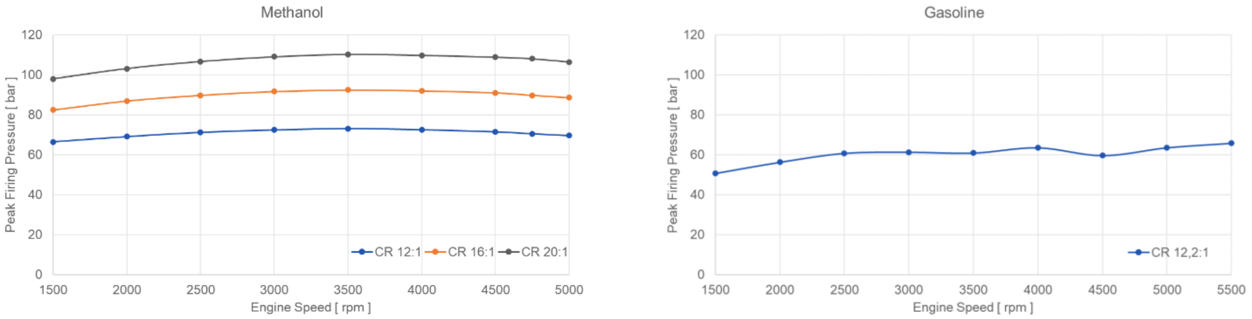


Figure 15: Peak firing pressure simulation methanol (left) and gasoline (right)

With these values we went into the Boost simulation to identify the power and efficiency potential of the ZVG with the use of 95 octane gasoline and methanol. The simulation shows a power output range of 13kWe to 45kWe for Gasoline and 16kWe to 54kWe for Methanol over the speed band from 1,500rpm to 5,000rpm. (Figure 16 shows shaft power for gasoline and methanol) Furthermore, the Brake Efficiency of the ZVG was simulated for both fuels with best points of 37% for the low-cost gasoline application and 40.5% for the methanol application. (Figure 17 shows the shaft power for gasoline and methanol)

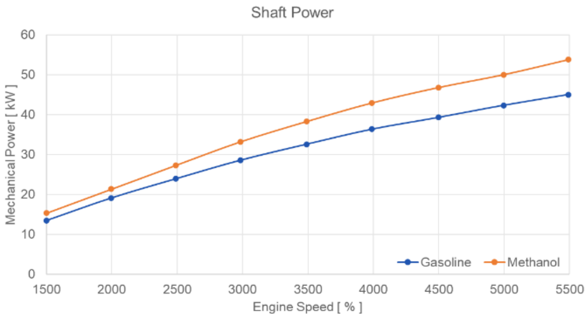


Figure 16: ZVG shaft power for gasoline and methanol

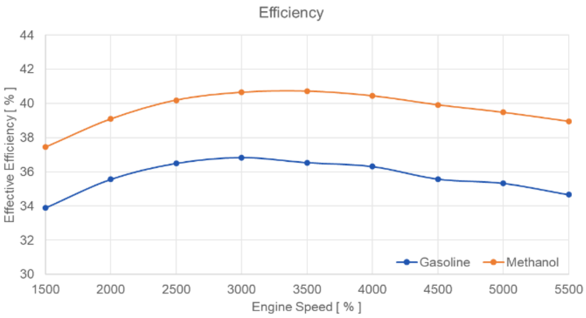


Figure 17: ZVG Efficiency for gasoline and methanol

(Figure 18 shows the design of the pistons for gasoline and methanol) The values shown in the graphs are based on the low-cost ZVG design described in chapter 3. This design is technically simplified to minimize complexity, size and production cost and includes no measures on the valve train or exhaust system to optimize system efficiency. The ZVG shows the potential to further improve the efficiency by additional increases of complexity and system cost.

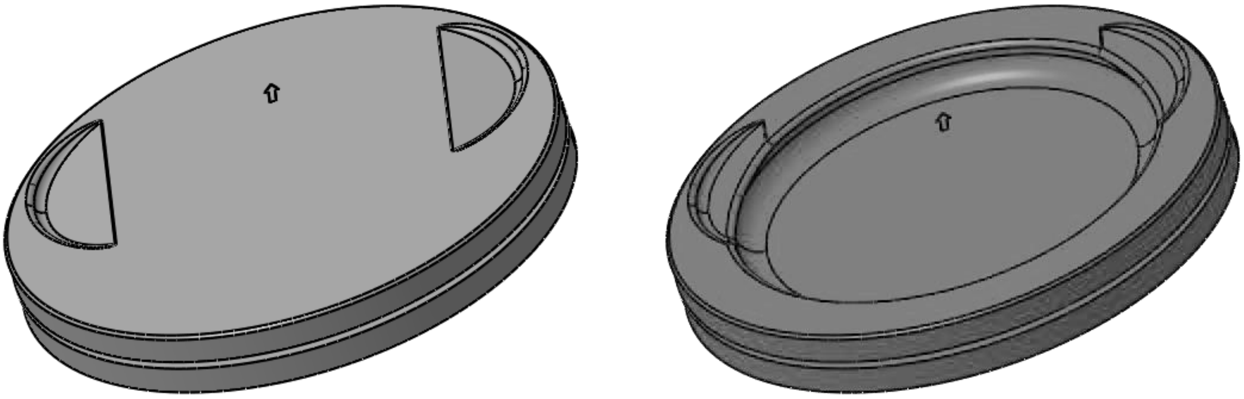


Figure 18: Methanol Piston with CR 20:1 (left) and Gasoline Piston with CR12:1 (right)

4.4 Use of an aluminum cylinder block with a clearance compensation system for the steel gears of the main drive to compensate the different elongation of the aluminum housing and the steel gears over the engine temperature operating range

Because the ZVG was designed for the use in a serial hybrid system, we have defined an overall load profile for the durability calculation based on test results we have generated with our demonstrator vehicles, results out of vehicle simulation with various driving profiles, as well as load data from customer requirements. These load data combined with its operation frequency was used as a baseline for the design and durability simulation of the ZVG. (Figure 19 shows ZVG operation time and load)

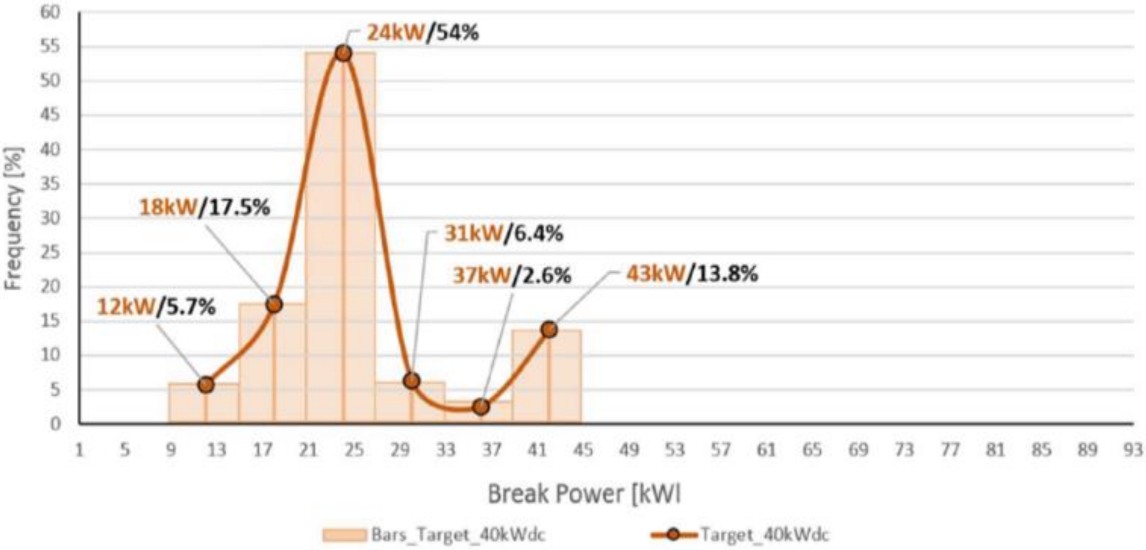


Figure 19: ZVG operation frequency and load points for serial hybrid application

To ensure the lifetime target of 2,000 operating hours for the volume design ZVG, AVL has carried out a load simulation of the complete ZVG main body based on the gas forces from of the simulation for methanol, the temperature behavior during operation, as well as safety margins for serial application. After several optimization loops, the final design of the ZVG fulfils the lifetime target of 2,000h based on the defined load profile. (Figure 20 shows the setting for the FE simulation)

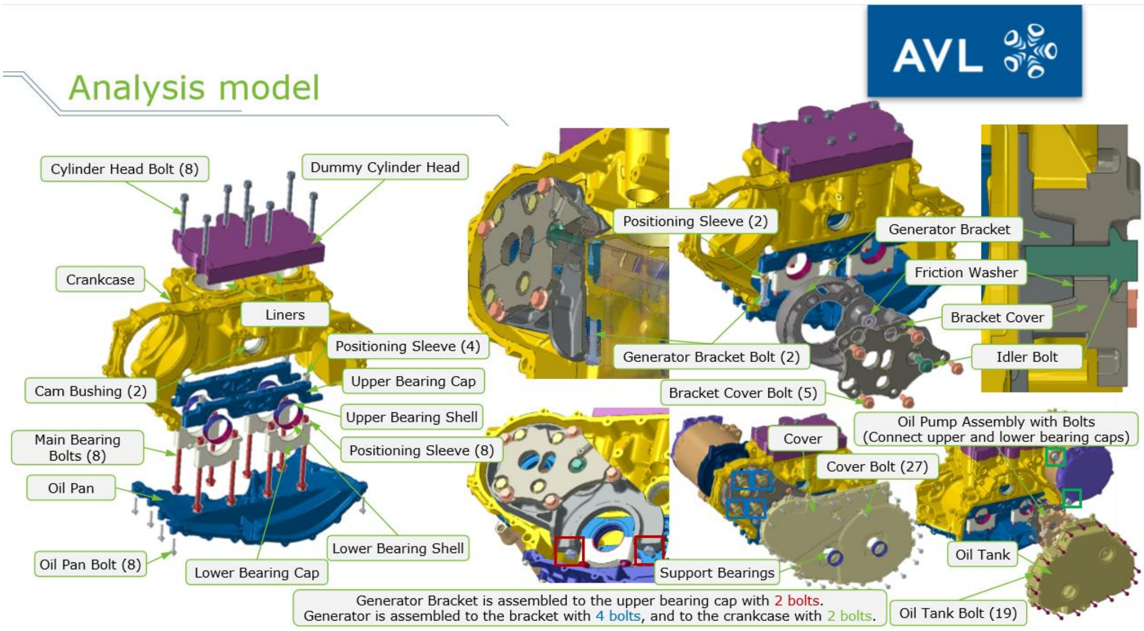


Figure 20: Setting of the ZVG for the FE simulation

The simulation has shown the gear train between crankshaft and generator as a weak point due to the temperature elongation between the aluminum cylinder block and the steel gear train. This problem caused a new solution by using a steel cartridge to carry the gear set as well as the generator system to decouple the train from the cylinder block. The design of the cartridge is based on a two-part design with a frame carrier and a screw cover. (Figure 21 shows the gear train cartridge)

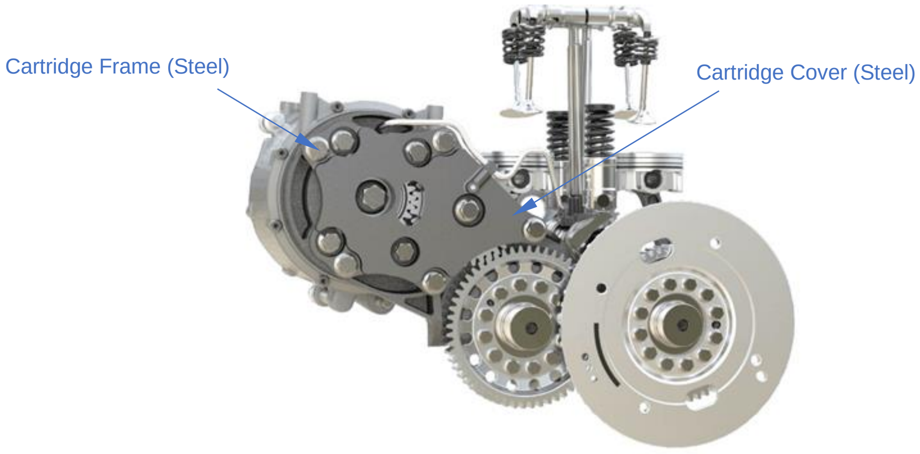


Figure 21: Gear train cartridge

Based on the high load of the main gear train due to the system dynamic, several optimization loops had to be carried out. The final design shown in Figure 22 fulfils the target requirements and shows the desired durability values.

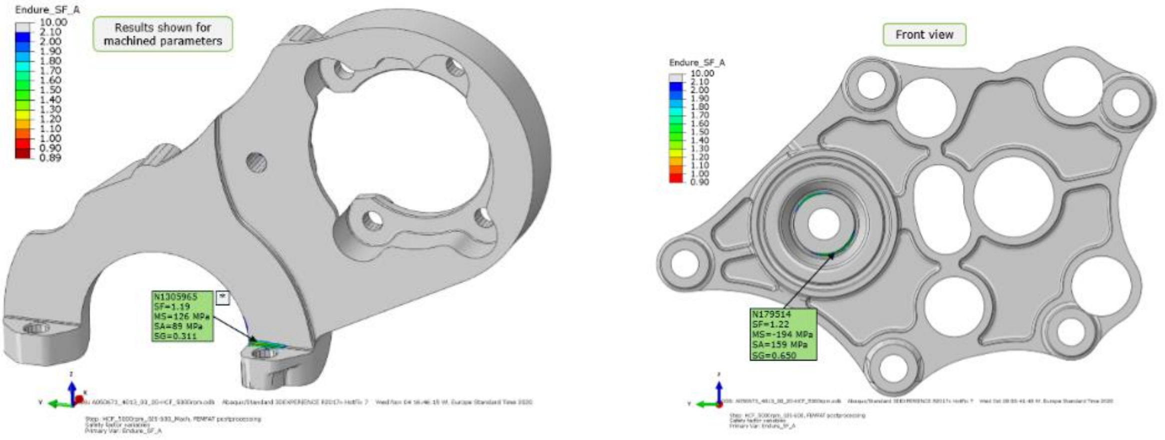


Figure 22: Simulation values of the final cartridge design

Alongside the decoupling function, the cartridge is carrying a radial adjustability function for the intermediate gear to adjust a defined tooth clearance between the intermediate gear and the generator and crankshaft gear. Due to the high dynamic of the gear train, the clearance between the gears is a significant factor for the gear tooth load and finally the durability. Based on the setting we have carried out several dynamic simulations with varied clearance to identify the required clearance and a compromise between load and adjustability due to production and assembling tolerances. (Figure 23 shows the gear clearance investigation results) The simulation shows that a clearance of 50µm will keep the load values for all applications within the lifetime target values. Clearance values in the range of 100µm will work with a load reduction of the ZVG in the speed point of 2,500 rpm to reduce the tooth load.

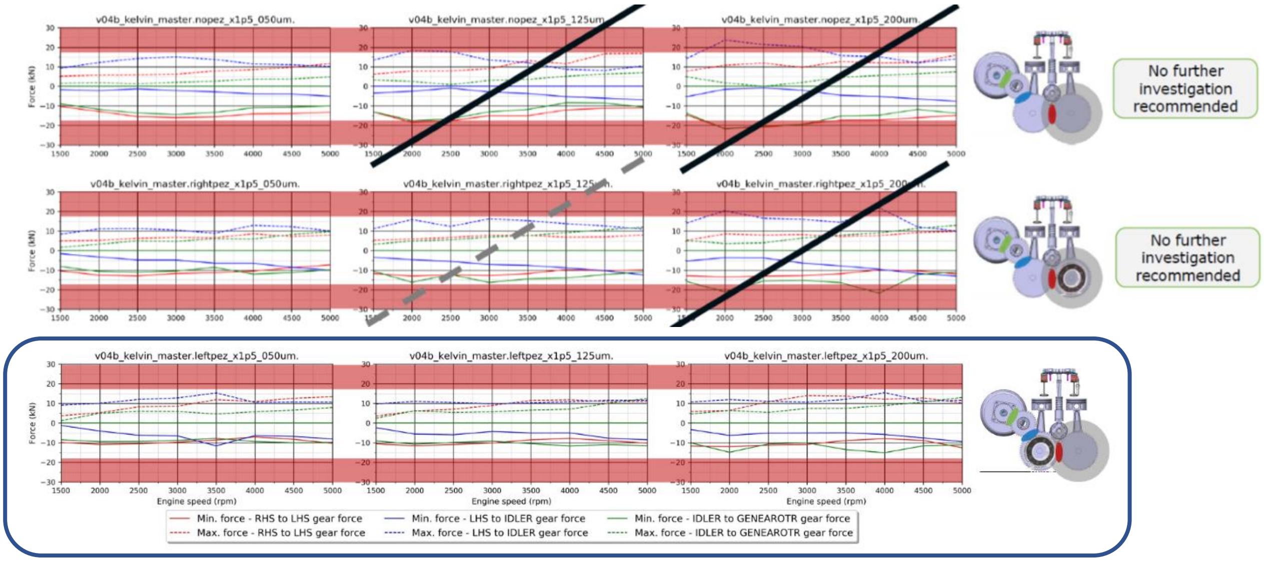


Figure 23: Gear clearance investigation

Finally, the following simulations and calculations of the main ZVG functions have been carried out, proven, and released alongside the results explained in the previous chapters:

Burning Process with:
Charge exchange
Fuel management
Combustion process
Valve timing

FEM with
Stress
Bearing
Bolts
Fatigue
Thermal impact

ZVG Cooling
Lubrication
Blow by venting
Exhaust system

4.5 Design of an acoustic insulation box with access to the main service parts of the ZVG

The design and the results of the ZVG simulations and test results have shown that the system is working without vibrations (due to full compensation of first end second order and the ability to compensate higher orders) and external rolling torques. To enable BEV-driving behavior with operating ZVG, it was necessary to also reduce the airborne noise generated by the combustion process. With the first sketch the ZVG was designed in a rectangular “shoe box” design to enable the application of a simple and effective acoustic insulation box with minimized interfaces to the ambient. With the first samples (HICE and ZVG A-Sample) we have collected data and experiences with noise insulation measures which have been transferred to the ZVG B-Sample design. (Figure 24 shows the impact of the insulation box on the airborne noise emission)

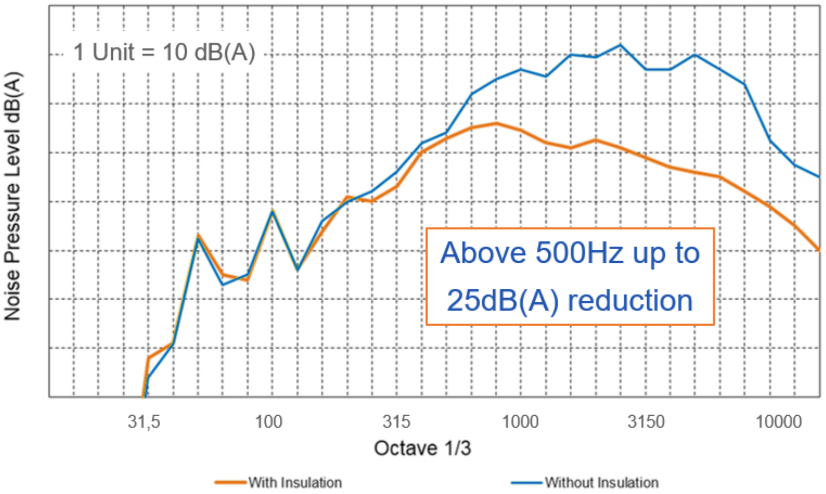


Figure 24: Airborne noise reduction due to insulation box

Measurement with the ZVG A-Sample in an acoustic chamber has shown a noise reduction value of up to 25dB(A) for higher frequent excitations starting at 500Hz. By the selection of the insulation material or combination of different materials an adaptation of the operation band is feasible. (Figure 25 shows the final design of the insulation box for the ZVG B-Sample.) The box is designed as a three-shell part where the top part is removable for service access to the ECU, spark plugs, ignition coils, fuses, inverter and oil service.

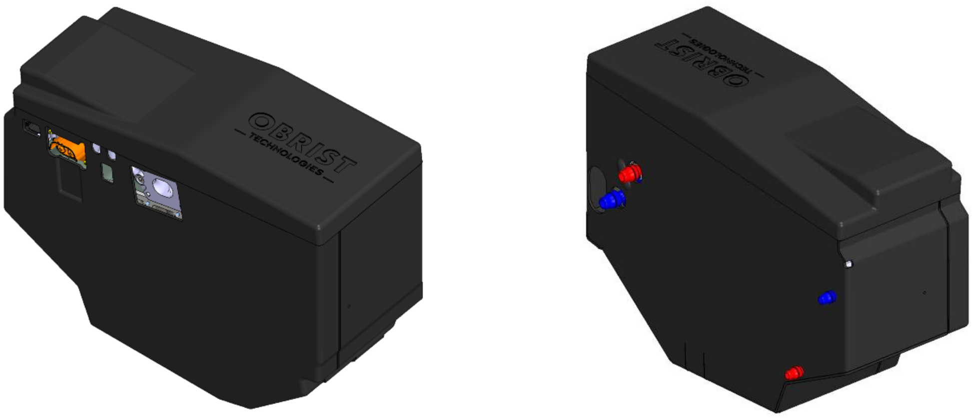


Figure 25: Three-part acoustic insulation box

5 Test Bed installation and start up of the ZVG B-Sample

Figure 26 and 27 shows the ZVG installation on the AVL start-up test bench. The ZVG was installed without insulation box, for a better access for the additional bench sensors, and the compact exhaust system. A first successful fire of the ZVG was carried out and test results will be available for presentation at the “Wiener Motorensymposium”.

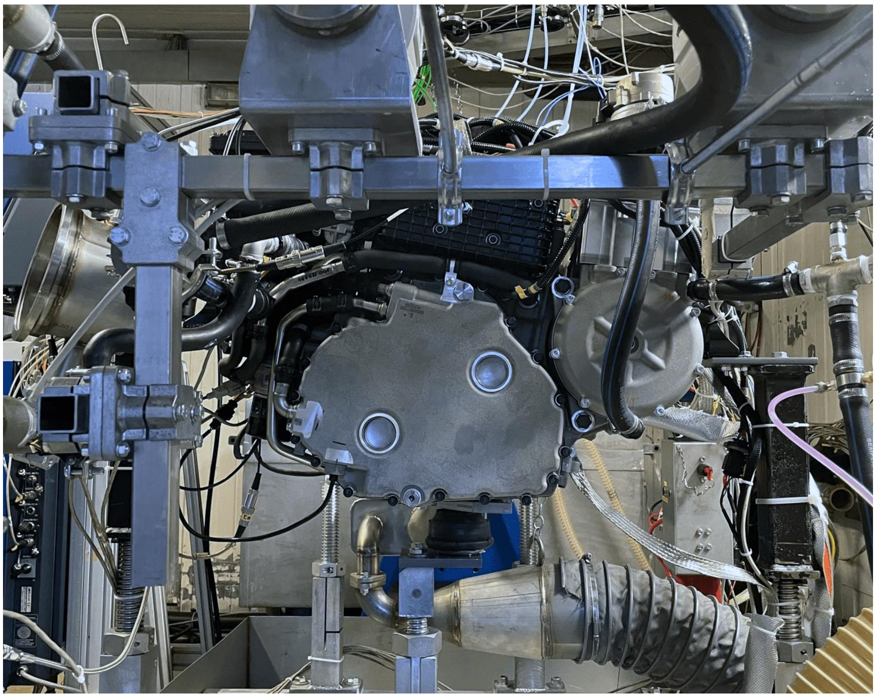


Figure 26: Rear view to the ZVG

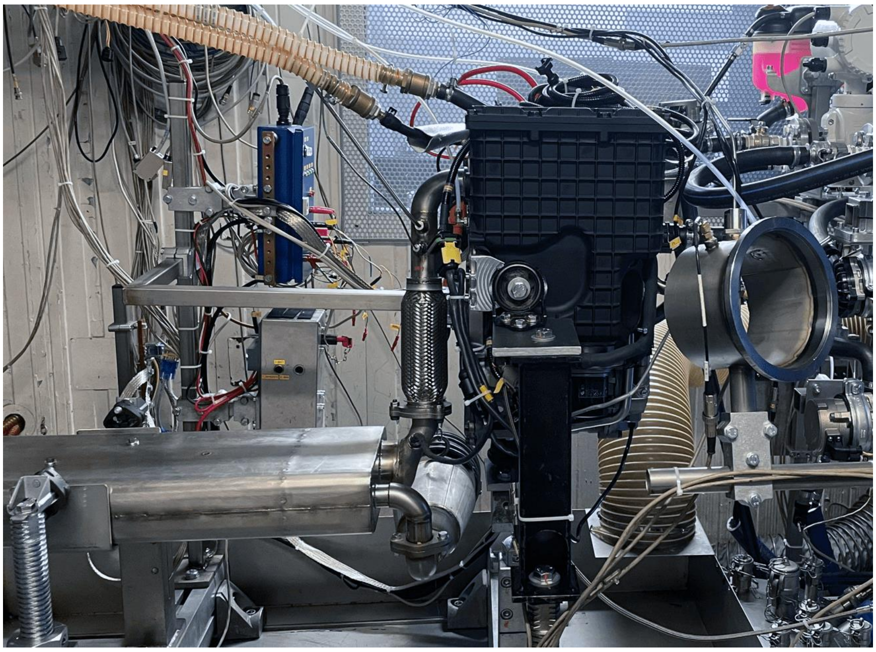
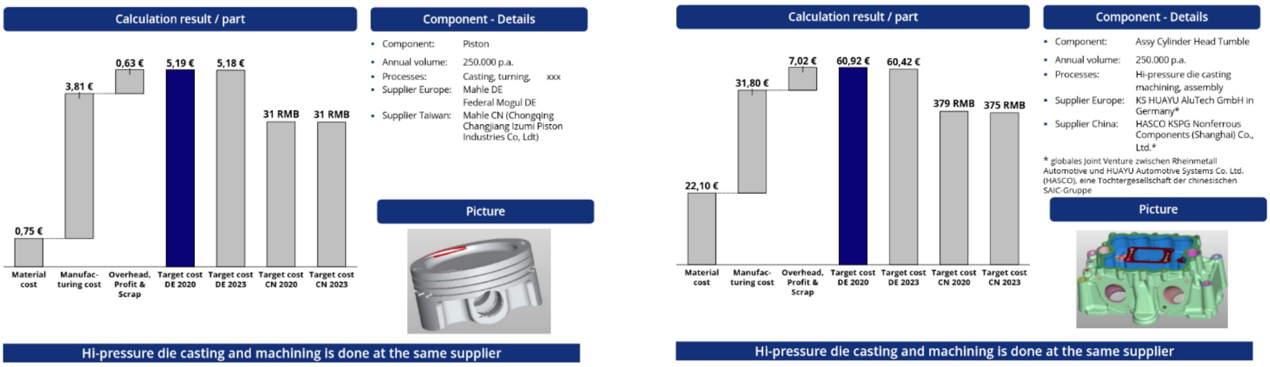


Figure 27: Side view with compact exhaust system

6 <u>ZVG cost calculation</u>

With the start of the ZVG B-Sample development, and aside the technical specifications, we have defined a material cost target for the mechanical parts of 550 € for a production volume of 250,000 Units/year over 8 years. In cooperation with Polarix Partner, we carried out a cost analysis for the ZVG based on production in Europe and alternatively in China. The production cost calculation includes material cost, labor cost, manufacturing cost and overheads. (Exemplarily, we have shown the cost calculation values for the cylinder head and the piston in Figure 26.)



Calculation result / part

Component - Details

- Component: Piston
- Annual volume: 250.000 p.a.
- Processes: Casting, turning, xxx
- Supplier Europe: Mahle DE
  Federal Mogul DE
- Supplier Taiwan: Mahle CN (Chongqing Changjiang Izumi Piston Industries Co, Ldt)

Picture

Hi-pressure die casting and machining is done at the same supplier

Calculation result / part

Component - Details

- Component: Assy Cylinder Head Tumble
- Annual volume: 250.000 p.a.
- Processes: Hi-pressure die casting machining, assembly
- Supplier Europe: KS HUAYU AluTech GmbH in Germany*
- Supplier China: HASCO KSPG Nonferrous Components (Shanghai) Co., Ltd.*

* globales Joint Venture zwischen Rheinmetall Automotive und HUAYU Automotive Systems Co. Ltd. (HASCO), eine Tochtergesellschaft der chinesischen SAIC-Gruppe

Picture

Hi-pressure die casting and machining is done at the same supplier

Figure 28: Production cost calculation for cylinder head and piston

The calculation ended up with a cost value of 520€ for the mechanical parts. For a fully functional ZVG we had to add the costs for the electrical parts: inverter, generator, and ECU as well as exhaust system with catalytic converter and insulation box. The production cost for the ZVG (40kwe) ended up at 998€ as an average value between production in Europe and production in China. (Table 2 shows the cost overview of the ZVG (40kWe))

			kUnits per Year
	Cost Units		250
0.1	1 Generator / 1 Inverter		302
0.2	Base Engine		520
0.3	3 Way Catalytic Converter		50
0.4	Exhaus System		40
0.5	Insulation Box		10
1	ZVG Material Cost		922
2	Direct ASSY Cost		76
3	Production Cost Target		998

Table 2: ZVG (40kWe) cost overview