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Greenhouse Gas Emissions Reduction on High-Speed Large Engines

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

High speed large engines continue to be the basis for for land-based stationary, transportation, and marine application power systems. The drivers to reduce greenhouse gas emissions for these power systems have increased significantly in recent years with market price upward trends for conventional fuels and strategies towards low and zero carbon fuels.

This paper describes the design, analysis, and testing of a new high speed large engine (HSLE) with the primary target to reduce GHG emissions through the following approaches:

a) To maximise the efficiency of conventional fuels by combustion means
b) To develop a platform for competitive BMEP low pressure H2 port gas admission
c) To maximise base efficiency through optimised friction and minimised pumping losses.

A new engine platform power cylinder was designed for high peak firing pressures up to 330bar and BMEP capability up to 35bar while retaining state-of-the-art durability requirements. High cylinder pressures are a key enabler to increase combustion efficiency and this paper will detail the design features and CAE analytical results for key components.

Testing results obtained on a single cylinder engine will be presented for conventional fuels demonstrating combustion-efficiency based GHG emissions improvements achieved when utilising the high cylinder pressure potential. Test results from the single cylinder engine will be summarised demonstrating efficiencies beyond 50% for given continuous ratings.

Hydrogen combustion with large engines mostly utilise low pressure gas admission upstream of the cylinder head, typically in the intake ports. Operating BMEP levels can be limited by combustion anomalies and the resulting peak cylinder pressures. Direct injection high pressure systems are under development for medium speed large engines to realise BMEPs approaching those for conventional fuels but remain a challenge for high-speed large engines due to system cost and availability. This paper will discuss combustion investigations performed with single cylinder engine testing on the new HSLE single cylinder platform with a key objective to demonstrate as high BMEP as possible with realistic boundary conditions relevant to a multi-cylinder engine. A high cylinder pressure design limit was a key enabler for high BMEP operation. The HSLE spark-ignited, port admission H2 engine operated up to 18 bar BMEP on 100% hydrogen.

This paper will discuss design features that were implemented on the HSLE to reduce friction and pumping losses as a means to reduce specific fuel consumption when operating on conventional fuels, ergo CO2 emissions. Friction parameter studies were developed to document potential and realised improvements by design concept selection and by design optimisation. In all cases, friction was equated to that represent an equivalent V16 multi-cylinder engine.

In conclusion, the paper surmises that the next generation of high-speed large engines require advanced design features together with advanced combustion systems to realise lowest GHG emissions with conventional fuels and to enable competitive power densities on zero carbon fuels.

1 INTRODUCTION

The European Union has agreed to support a 1.5°C global temperature increase target cap by 2050 with a multi-faceted approach to in GHG (Greenhouse Gas) emissions reduction. Engine OEMs and operators face an uncertain and potentially turbulent outlook regarding fuel types regarding availability, end-user acceptability, and costs.

While combustion engines are anticipated to retain a significant portion of the maritime, rail and grid & island power generation business, the fuel type is expected to diversify from largely oil and natural gas to include hydrogen and hydrogen-based fuels such as ammonia and methanol, plus other e-fuels for zero carbon emissions. For industry segments such as marine transportation, the transition towards decarbonisation is expected to result in a diverse mix of fossil and low carbon fuels [1].

As production and distribution networks are more comprehensively established for these hydrogen-based fuels in the upcoming years, commercial pressure is expected to be placed on current diesel and natural gas fossil fuels with taxation levels expected to increase. Therefore, there is a renewed impetus for combustion engine efficiency increase.

This paper describes the design of a new high speed large engine (HSLE) power cylinder unit with displacement of 5.2L per cylinder. The intention of which was to develop a durable, high-power-density, high-efficiency basis for multi-cylinder engines.

Results from the mechanical development testing will be shown together with correlations with performed analysis. Summary results from the performance engine testing will then be discussed. Finally, a summary of the work performed to optimise the mechanical efficiency of the engine related to both core components and ancillaries relevant to multi-cylinder engines.

2 OBJECTIVES

The general target to reduce GHG emissions was considered through the following approaches:

a) To maximise the efficiency of diesel and gas fuels by optimised core engine design and combustion

b) To demonstrate a competitive BMEP low pressure H_2 port gas admission open-chamber spark-ignited

c) To maximise base engine efficiency through optimised friction and minimised pumping losses.

The following sections detail more the specific design, validation, and performance targets.

2.1 Engine Performance Targets

The following performance targets were established based on competitive benchmarking and AVL's forecast for a competitive next generation engine platform.

- Diesel BSFC target of 168 g/kWhr for a 50Hz continuous genset rating with 170kWm/cylinder
- Diesel BSFC target of 172 g/kWhr for a standby power generation and marine rating of 270kWm/ cylinder
- Gas efficiency of >50% for an electrical power generation rating of 210 kWm/cylinder
- Demonstrate hydrogen combustion at a competitive BMEP with port admission, pre-chamber spark ignition
- Frictional and pumping losses optimisation minimisation

Performance and emissions and mechanical investigations were to be performed on single cylinder engine with a highly advanced power cylinder unit. In consideration of test engine neutrality and high BMEP and PFP capability requirements, AVL designed a completely new clean-sheet power unit. This will be described in the following chapters.

2.2 Power Cylinder Unit

AVL designed a new clean sheet engine power cylinder unit to be used as a platform for the performance and mechanical development testing. The design and analysis of the new base engine was performed by AVL with support from commercial partners.

The high-level engine design specifications are given in Table 1. These were determined through thermodynamics pre-investigations as part of the internal design process.

Table 1 Engine Specifications

Engine Parameter	AVL175
Bore [mm]	175
Stroke [mm]	215
BMEP [bar]	35 (D), 32.5 (G), >14 (H_2)
Rated Speed [rpm]	1500 & 1800
Maximum Torque Speed [rpm]	1200
Peak Firing Pressure [bar]	330
Max Rated Mean Piston Speed [m/s]	12.9 (1800rpm)
Compression Ratio Diesel	Range 16 - 20:1
Compression Ratio Gas / H_2	Range 12.5-14.5:1
Max Diesel fuel injection pressure [bar]	2600

2.2.1 BMEP target

Increasing BMEP is a known enabler for fuel efficiency improvement with the assumption that FMEP and PMEP do not increase disproportionately. The assumption that frictional losses increase proportionally with BMEP for a given operational speed, has been shown to be partially incorrect [2] since an increase in operational BMEP will drive increasingly higher demands on sub-systems which thereby increase losses and reduce the effective efficiency. The dashed line in Figure 1 represents an ideal trend with the solid line considering an influence of increasing FMEP.

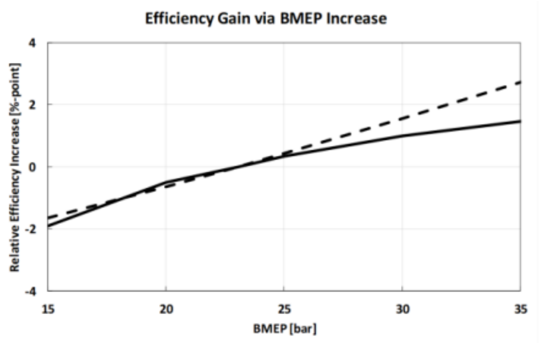

Figure 1: Brake thermal efficiency versus BMEP [2]

As BMEP increases, cooling capacity requirements increase for the engine, requiring increased cooling water flow and consequently higher rate cooling water pumps, which are engine-driven for many high-speed engine applications.

Charge air consumption will increase with BMEP for a given lambda therefore cooling capacity for charge air cooling will increase proportionally. At a certain BMEP level, a change to 2 stage turbocharging will be a necessity. For engines with two stage cooling, the rejected heat may be divided between the engine water circuit and a separate low water temperature circuit.

For diesel fuel injection systems, greater quantities of fuel admission will mandate the common rail fuel pump driving power requirements, either by increased consumption from the fuel rail with the existing high-pressure pump(s), increased capacity pump(s) or potentially an additional pump.

AVL considered the following BMEP targets during the design and development testing of the new power cylinder:

- Diesel 50Hz continuous genset application with 170kWm/cylinder (26.3bar BMEP), realisable with SSTC
- Diesel high power standby power generation and marine applications with 270kWm (35bar BMEP) requiring TSTC
- PCSI Gas 50Hz standby power generation application with 210 kWm/cylinder (32.5bar BMEP).
- H_2 (low pressure port injection) power generation >14 bar BMEP

2.2.2 Peak Firing Pressure

AVL performed thermodynamic studies to investigate the influence of various compression ratios and lambda levels on engine efficiency (BSFC), exhaust gas temperatures, and resulting peak firing pressures. The following correlations were derived:

- An increase of the EAR (lambda) by 0.1 units correlates with a reduction of BSFC of 1g/kWh
- An increase of the compression ratio by one unit correlates with a reduction of the BSFC by 2g/kWh

For a given target BMEP of 35bar for the highest diesel rating, it was concluded that a lambda of 2.2 should be targeted which requires a PFP of 330 bar. During the thermodynamic investigation, the competitiveness of the new engine was checked against database engines. Figure 2 shows the benchmark of the AVL175 power cylinder BMEP and PFP targets vs AVL database of similar bore size engines from the past 10 years. The new power cylinder falls on the upper envelope of the benchmark trend and it confirmed a natural progression in the trend for future engine capabilities.

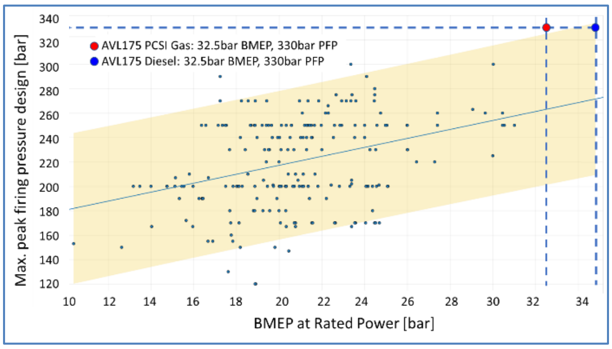

Figure 2: Benchmark of PFP vs BMEP

2.2.3 Mean piston speed

Mean piston speed (MPS) was investigated according to state-of-the-art levels of <13m/s at 1800rpm rated speed and with a target rated power of 270kW per cylinder. With consideration to PBI (Piston-Bore Interface) friction and durability, a stroke of 215mm was selected resulting in 12.9mm/s and 10.8mm/s at 1800rpm and 1500rpm respectively.

The MPS x BMEP was compared with 35bar BMEP against benchmark from AVL database values, as shown in Figure 3, and found to be in a competitive, but acceptable, extension range of the trend upper envelope.

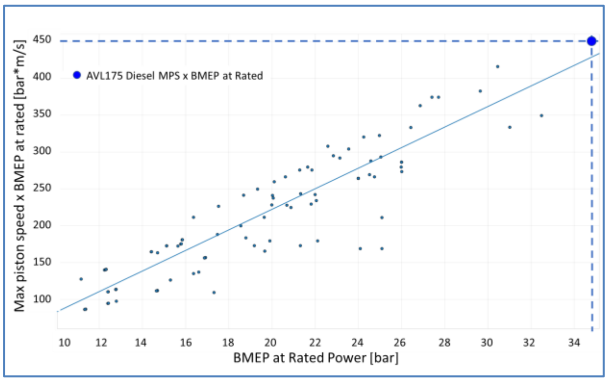

Figure 3: MPS x BMEP versus BMEP Benchmark

3 ENGINE PLATFORM

AVL designed a completely new power cylinder unit to be utilised as a neutral basis for performance and emissions research and for mechanical development investigations. The PCU is shown in Figure 4 and was, however, not only designed for research activities but with specific intention to be feasible for multi-cylinder engine production. Where relevant to a multi-cylinder configuration, for example the crankshaft dimensions, valvetrain configuration, a 20-cylinder vee engine configuration was taken as a basis for component design.

Figure 4: AVL175 Power cylinder unit

Manufacturability with conventional production techniques was considered in the engine design to be relevant to production engines and to provide a viable basis for application in a multi-cylinder engine. An overview of the manufacturing processes used is shown in Table 2.

Table 2: Power Cylinder Manufacturing Processes

Component	Manufacturing
Cylinder head	Sand cast CGI
Cylinder liner	Gravity cast iron
Crankcase upper (block)	Sand cast ductile iron
Piston	Crown & skirt, friction welded
Conrod	Forged design, serrated split
Crankshaft (SCE)	Fully machined
Crankshaft (V20)	Forged design, filet hardened

Durability targets equivalent to current state-of-the-art engines are shown in Table 3. These were referenced during the high cycle fatigue analysis performed in the design phase.

Table 3: Power Cylinder Durability Targets

Parameter	Hours TBO
Minor overhaul	20,000
• Conrod bearings	
• Piston, rings, liner	
• Valves and valve seats	
Major overhaul	40,000
• Main bearings	

The following sections summarise the design features of the main components with considerations for efficiency, performed analysis and key test measurement results.

3.1 Cylinder head

The design of cylinder head considered a common casting for the diesel variant, a gas-fed pre-chamber spark ignition variant and a passive pre-chamber/open chamber spark ignited gas.

Casting material was selected as compact graphite iron GJV-450 for 330bar PFP. A common casting was feasible for diesel and gas. If required, GJL material would also be feasible for up to 250bar PFP. Gienanth GmbH, as casting partner, performed filling and solidification simulations to ensure the desired material properties were achieved, particularly at the highly loaded fire deck region [3].

Cross-flow port design was selected for highest flow efficiency with low swirl design. Cross-flow is preferential for more uniform heat distribution into the cylinder head when compared to a u-flow design.

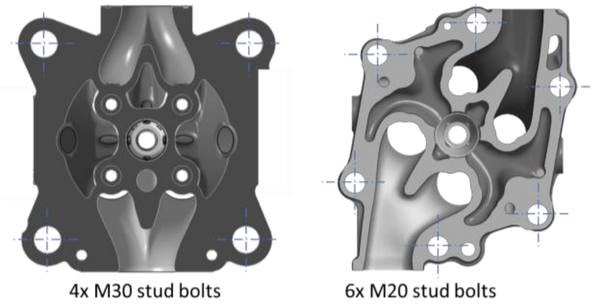

Figure 5: Port orientation and bolt location

Bolt configuration selection considered sealing pressure against 330bar PFP with minimisation of liner distortion under clamping loads. 6 head bolts were selected for more homogeneous loading. Hydraulic tightening is commonplace for such engines but the use of mechanical torque tightening with HYTORC nuts allowed improved accessibility and further enabled a reduction of the bolt size from M24 to M20 by eliminating torque stress on the studs and reducing pre-tension losses. The centrifugally-cast liners were manufactured with state-of-the-art plateau honing by M. Jürgensen GmbH & Co KG.

The inlet and exhaust ports were orientated at 45° around the vertical axis to help reduce cylinder distance and to allow simplified valve actuation components with low inertia, necessary for high valve opening and closing accelerations mandated for highest engine efficiency. Figure 5 shows the comparison between a four-bolt design concept with M30 stud bolts and a 6-bolt design concept with M20 stud bolts. The gasket sealing pressure was evaluated with simulation with cold load, gas pressure and under hot load. Figure 6 shows an extract of the simulated gasket sealing pressures on the upper and lower gasket surfaces under cold conditions, with and without gas forces. As comparison the gasket pressure measurement taken during assembly is also shown. The proximity to bolt locations is clearly evident but in all cases met the AVL minimum sealing pressure requirements.

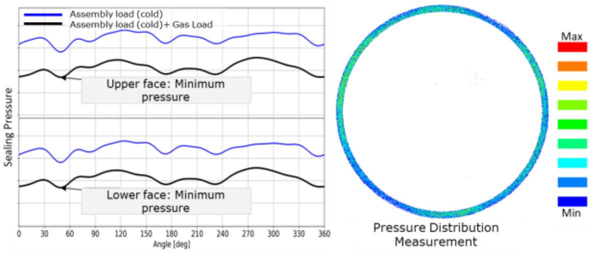

Figure 6: Simulated and measured gasket pressure distribution

The cylinder head strength was optimized with special consideration for the heat transfer capability by means of patented cooling and force-direction design technologies. CFD analysis was used to optimise the cooling of the fire deck and the region around the central injector or gas pre-chamber [3], critical contributor for reduced pre-ignition risk at high BMEP gas and pre-mixed H_2 combustion.

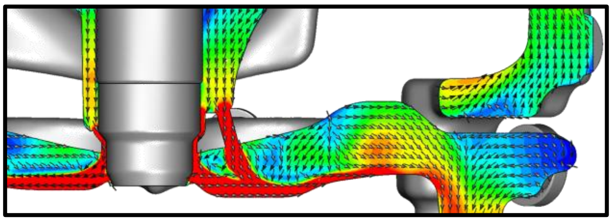

Figure 7: Cylinder head cooling water flow velocities CFD

Cooling of the fire-deck in the region of the valve bridges is critical to achieve the required thermomechanical fatigue life cycles. The AVL Top Down Cooling concept was applied to the new power cylinder unit to reduce the maximum temperatures in structurally critical areas within the cylinder head [4]. An advantage of the cooling concept is that it enables precise control of cooling water flow through the cylinder head, demonstrated earlier on a 30bar BMEP 300bar PFP power unit [5]. For the AVL175 cylinder head, the flow distribution was tailored by means of a drilled bypass to the Exh-Exh bridge, shown in Figure 7. The simulated surface temperatures were verified by an instrumented test with thermocouples placed at varying depths. The measurements were then extrapolated to surface positions and the temperatures compared for the 35 bar BMEP operating condition and confirmed acceptable margin to the development limit.

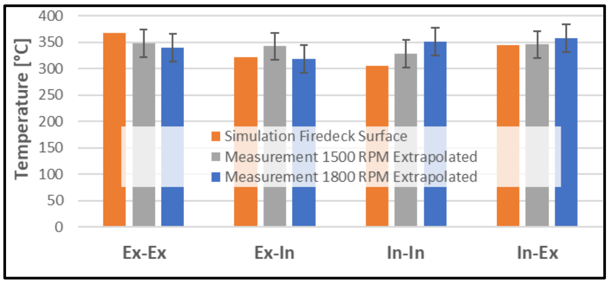

Figure 8: Measured vs. simulated valve bridge temperatures

3.1.1 Port Geometry

The intake ports for both diesel and gas/H_2 variants were designed with high mean flow coefficients and low swirl. Diesel combustion used high fuel injection pressure to achieve fast diffusion combustion. PCSI gas used pre-chamber combustion plumes to initiate strong multiple ignition locations. Figure 9 shows the mean flow coefficients as measured on a flow bench with standardised valve lift curves and compared against cylinder port measurements of benchmark engines. It can be seen that the resulting flow performance is above the statistical regression line.

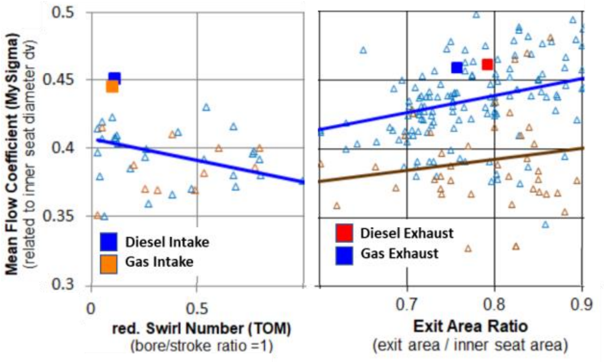

Figure 9: Port flow measurements

3.3 Conrod

The conrod was newly designed for the AVL175 due to the high PFP requirement. The forged design was fully machined for the manufacture of the SCE testing. AVL performed EHD bearing and FE strength analysis to determine the geometries and worked closely with Miba GmbH to evaluate material bearing geometries and materials [6]. The large end bearings achieved total pressure requirements for sputter bearing type of below $420N/mm^2$ over the complete speed range. Asperity contact pressures with the nominal design PFP requirement were achieved at 330bar PFP at both rated power speeds, 1500rpm and 1800rpm and highest BMEPs. For highest engine efficiency, the bearing geometries were designed to meet the mechanical and thermal loading requirements and durability targets without excessive margins.

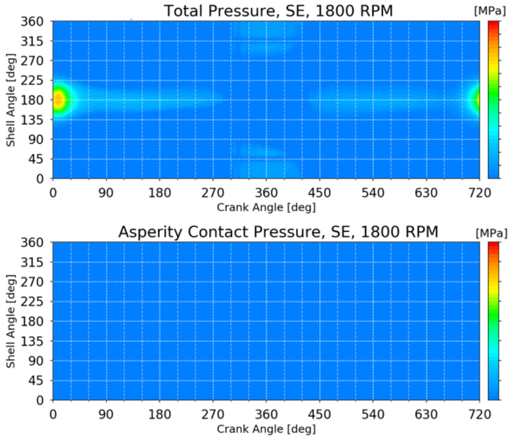

Figure 10: EHD analysis results for conrod small end bearing

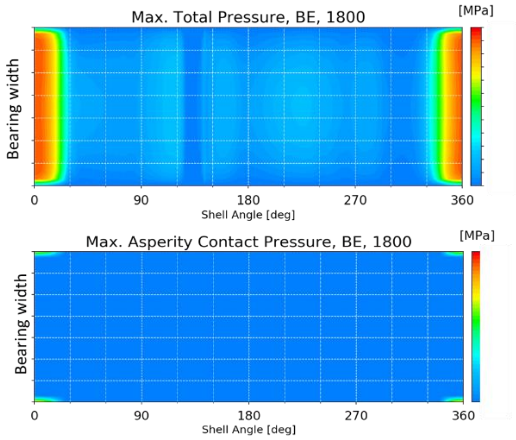

Figure 11: EHD analysis results for conrod large end bearing

Extensive analysis was performed to optimise the design of the conrod small end and large end bearings. The maximum total pressure and asperity contact pressures were evaluated over a wide speed range of full load operation and also low and overspeed conditions. An example is shown in Figure 10 of the conrod small end and in Figure 11 of the conrod large end bearing total pressure and asperity contact pressure results for 1800rpm 35bar BMEP 330bar PFP. Maximum pressure and asperity contact pressure were acceptable and the bearings were produced and installed in the SCE.

Figure 12 shows the inspection results from a planned teardown inspection after operation at high PFP which indicates even loading of the bearings and validates the analytical results.

Figure 12 Conrod large end (L) and small end (R) after initial high PFP testing

The conrod small end was designed specifically to be splash lubricated from piston return oil so to avoid, in addition to higher production costs, the need for a separate pressurised supply which would unnecessarily increase oil flow demand from the oil pump and efficiency losses. The bushing shape was optimised with EHD and with careful consideration of expected deformations during high peak cylinder pressures. Both mechanical loading and thermal loading requirements were satisfied during analysis investigations.

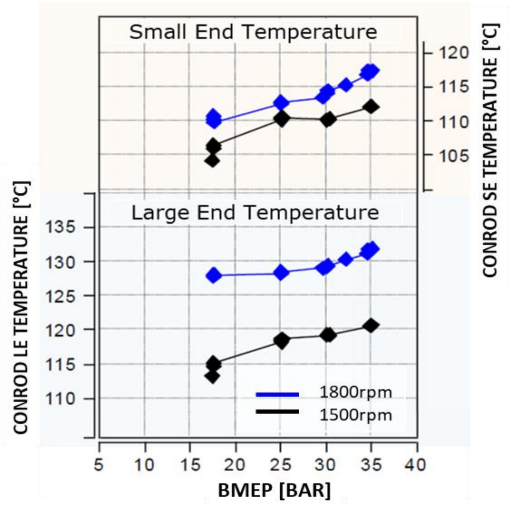

Figure 13: Telemetric bearing temperature measurements

Instrumented telemetric testing was performed with small and large end temperatures measured over a range of speeds and loads. Figure 13 shows the trends at 1500rpm (black) and 1800rpm (blue) at PFP limits up to 35bar BMEP. As expected, the temperatures trend upwards with BMEP and engine speed due to increased pressures and friction, particularly evident on the large end because of the increase in rotational speed. The temperatures showed close correlation to analysis predicted temperatures and within measurement tolerance. LE bearing is confirmed to be operating in a purely hydrodynamic regime, as the temperature is more influenced by speed than engine load.

3.5 Pistons

AVL was supported by Kolbenschmidt GmbH to develop new piston designs for the diesel and gas combustion. Both piston variants used a steel crown and steel skirt, friction welded together before final machining. To note, the pistons were designed without anti-bore polishing rings for the SCE testing, as the deposit formation from combustion would not increase to a notable level. The gallery design for the cooling of the piston crown was evaluated with heat input from AVL combustion CFD analysis. A boundary region was derived, considering structural and cooling requirements, for potential piston bowl shapes and enabled a variety of bowl geometries to be developed with CRs ranging from 16-19:1. Piston ring layout was performed by Federal-Mogul Burscheid GmbH and test hardware was also supplied.

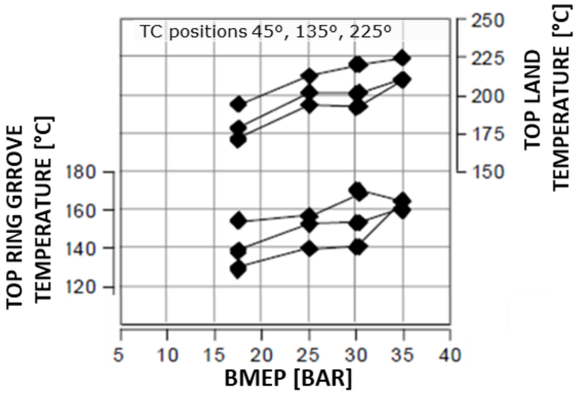

Figure 14: Telemetric piston temperature measurements

The simulated temperatures of oil-touched surfaces were below the limit for oil carbonisation. Instrumented telemetric temperature measurements were taken on the operational SCE at loads up to 35 bar BMEP operating on diesel fuel. Figure 14 shows an extract of the measurement data with thermocouple positions located in three positions radially at 45° (in line with exh-exh bridge), 135° (exh-in) and 225° (in-in). The highest temperatures in each case corresponded with the exhaust-exhaust orientation. Even up to 35 bar BMEP, piston temperatures were lower than the carbonisation guideline limit for a standard single grade SAE40 lubricating oil.

3.6 Valvetrain

Valvetrain actuation was via state-of-the-art pushrod actuation with roller followers, double springs with rotation caps underneath. Thermodynamic studies confirmed that engine performance behaviour is more responsive to improved intake valve lift in comparison with exhaust valve opening events, particularly with regard to Miller IVC events. Therefore, a cold-side camshaft was selected, as shown in Figure 15, for the valvetrain under consideration of a short actuation path for lowest inertia and higher stiffness for the intake valve actuation as a key enabler for highest efficiency intake valve lift curves.

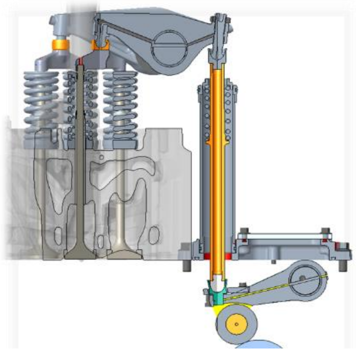

Figure 15: Valvetrain arrangement on AVL175

Valve dimensions were determined with close collaboration with Märkisches Werk GmbH to ensure key limits were adhered to for target durability achievement. With consideration of PFP and BMEP, valve seat surface pressure limits shown in Table 4 were defined for operation up to 330bar PFP.

Table 4: Valve seat pressure limits.

Engine Configuration	Diesel	Gas
BMEP [bar]	35	32.5
Valve seat surface pressure [N/mm^2]	140	160

For optimised valve lift profiles, first target valve lift profiles were determined via 1D Thermodynamics investigations. These were subsequently fully optimised with regards to opening and closing dynamics to maximise the opening and closing accelerations to avoid excessive component loads and decelerations to avoid contact loss. Figure 16 Illustrates the optimisation of three valve motion events for three different IVC timings.

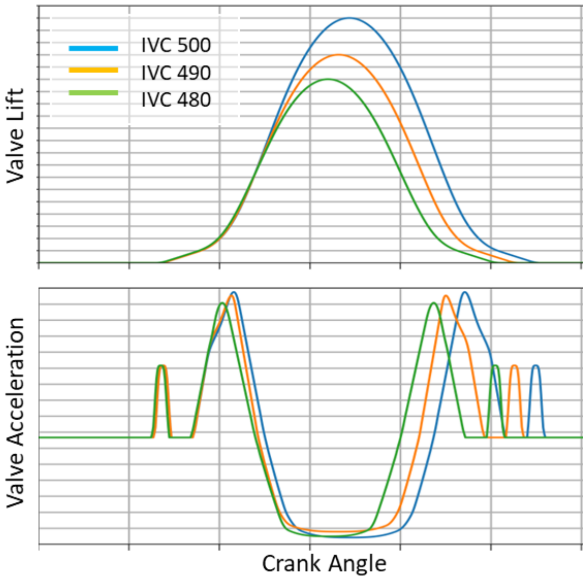

Figure 16: Optimisation of Valve motion

Camshaft intake profiles were developed and optimised with AVL EXCITE^{TM} with valve opening timings ranging from a strong Miller early closing event of 480°CRA to 580°CRA, representing a thermodynamically optimised valve closing timing.

In all cases, the camshaft profiles were optimised with careful regard to margin for contact loss, cam contact stresses and valve spring tangential stresses.

3.7 VIVT

One of the building blocks for reduced fuel consumption ergo reduced CO_2 emissions is application of a strong Miller intake valve timing (early closing). Common challenges with adoption of very early intake valve closing are cold starting under cold ambient conditions for mobile applications and a detrimental impact to the transient performance of the engine in operation, particularly for variable speed applications.

In order not to unduly limit the application of strong Miller timings beneficial for combustion efficiency, the consideration that a degree of variable valve timing could be applied if required. Many variable valve timing systems operate on a lost-motion principle leading to unrecovered energy transmitted to the valve actuation. AVL designed a new mechanical system for force transmission, not hydraulic, to avoid efficiency loss, shown in Figure 17.

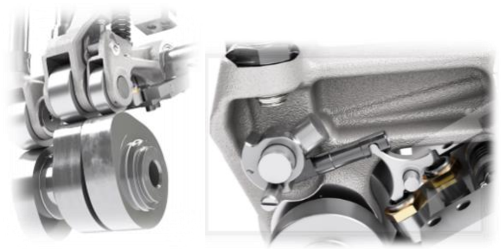

Figure 17 Variable Intake Valve Timing

The new patented design makes use of two intake cam lobes. Both utilise common cam flanks to open the intake valves, the cam movement acting to compress springs. The closing movement of the valve is then controlled by either cam lobe. The design results in robust valve actuation system with mechanical efficiency proportional to a conventional non-variable actuation system.

4 BASE ENGINE EFFICIENCY

The testing of the power cylinder was performed on a single cylinder engine which, by nature, has a higher friction level due to a large flywheel, oversize main bearings and a turret bearing to support such a flywheel and a mass balancing system required for the SCE. Conversely, oil and water pumps are electrically driven and the high-pressure fuel supply to the diesel injector is via an external unit. Therefore, a multi-cylinder friction model was developed to provide a plausible correlation to a multi-cylinder engine.

A friction-walk was performed for a V20 multi-cylinder model, starting with a plausible FMEP level of a state-of-the-art engine at 25bar BMEP, as shown in Figure 18. Additive design features were accounted for due to the increase in BMEP to 35bar and PFP to 330bar.

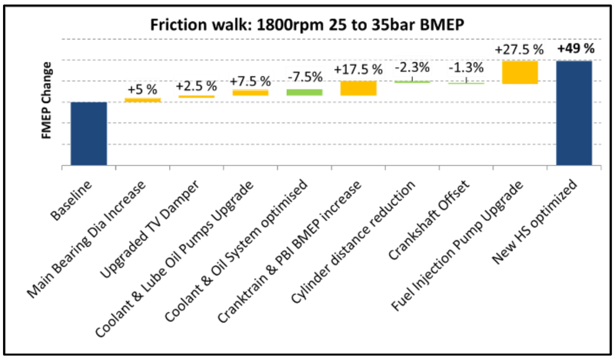

Figure 18: Friction walk for AVL175

Main and conrod bearing dimensions have a strong influence on resulting friction. Design of a new crank train layout must not only consider cylinder distance, bearing unit loads and minimum oil film thickness, but should also consider that friction is more influenced by bearing diameters. Latest bearing technologies could be enablers for reoptimized bearing dimensions for existing engine platforms.

Increased oil and water pump demands increase with BMEP and, if engine driven, influence base engine efficiency. For stationary high-power applications, the use of off-engine cooling water supply is common. For engine-driven water pumps, correct sizing and consideration of pump efficiency is important. Likewise, oil pump sizing should consider an appropriate margin for high oil temperatures and upper limit of bearing clearances.

Increased BMEP and PFP will influence crankshaft torsional vibrations and an appropriate sizing of crankshaft torsional vibration damper and resulting dissipated power will have an influence on FMEP. It is normal that TVD are re-sized within an engine family according to rating-specific requirements but is a trade-off against component commonality.

Piston-Bore Interface friction is strongly influenced by operating PFP due to piston side forces and piston ring forces against the cylinder liner. These are accounted for by default during engine calibration procedures where engine efficiency trade-offs against PFP will be investigated.

For diesel engines, the increased power requirements of the fuel injection pumps must be considered. These are somewhat proportional to volume flow and injection pressure demands.

A key takeaway is that friction-influencing design features related to BMEP and PFP should be sized or specified according to the intended use of the engine. Redundant capacity within the core engine design, if not utilised, should be carefully considered to increase engine efficiency. The use of non-common interchangeable components must be weighed against influences on product family complexity and costs. Friction modelling and optimisation investigation of friction-influencing components can have potential benefits for both new and existing engines.

5 SCE TESTING

The testing of the assembled AVL175 single cylinder engine, shown in Figure 19, was performed as part of the COMET Large Engines Competence Center programme together with multiple supporting scientific and industrial partners. Testing was divided into two programmes, one focused on performance and emissions, the second focused on mechanical development.

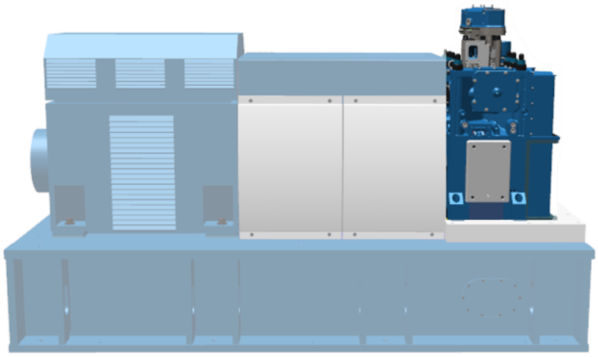

Figure 19: AVL Large Single Cylinder Engine

The new power cylinder assembly was installed on high-speed single cylinder engine, previously installed in the test facility, and coupled to an active dynamometer. A test matrix was created consisting of a composite of multiple ratings and applications. The performance and emissions data acquired could then be utilised for application relevant ISO8178 emissions cycles such as electric power generation (D2), non-road machinery (C1) and marine propulsion (E3).

SCE boundary conditions were created, representative of a V20 multi-cylinder engine with thermodynamics SCE-MCE modelling and a V20 MCE friction model was embedded in the testbed PUMA system. This included consideration of engine-driven oil and water pumps and fuel injection pumps, where applicable.

Measured engine-out emissions targeted most stringent regulations, such as EU Stage V Inland waterway transport, assuming state-of-the-art aftertreatment conversion rates. Aftertreatment conversion efficiencies were based on documented measurement data acquired separately to the SCE testing.

Mechanical development testing included series of assembly measurements, functional tests, durability tests and thermal surveys. Figure 20 shows examples of the instrumentation set-up for thermal investigations on the cylinder head using conventional instrumentation, and conrod bearings using telemetric temperature measurement.

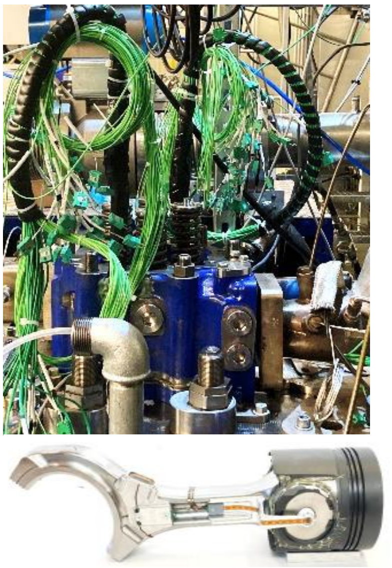

Figure 20: Thermal survey instrumentation

6 TEST RESULTS DIESEL COMBUSTION

A comprehensive research and development programme for performance and emissions was performed within the COMET funded EvoLET programme. With the close cooperation with Bosch AG, for the fuel injection system, a number of building blocks were evaluated and validated.

- Reduced combustion duration through variation of fuel injection pressure and nozzle spray hole configurations.
- Valvetrain optimized lift curves were investigated with various intake valve closing timings.
- Piston bowl shapes were investigated, and compression ratio layouts determined for 330 bar PFP for medium BMEP and high BMEP ratings, the boundary defined around 26 bar BMEP.

Figure 21 shows the summary results with SCE BSFC measurements at rated operating points and V20 MCE equivalents. For fair comparison with advertised BSFC values from most OEMs, the values are shown with 3% tolerance, less than the allowable 5%.

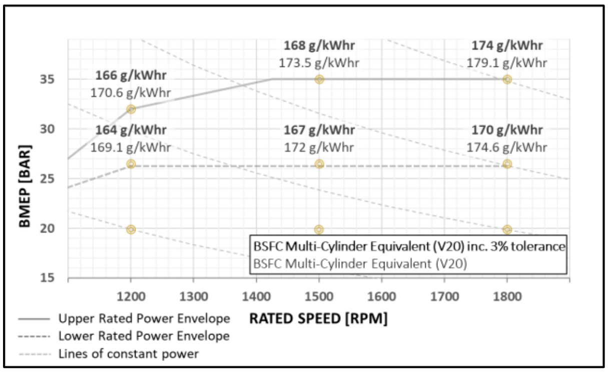

Figure 21: Rated operating point BSFC

The results show class-leading potential for fuel efficiency with MCE-equivalent rated BSFC rates of 167-168 g/kWhr at 1500rpm rated points and 170-174 g/kWhr at 1800rpm rated points.

For BMEP ratings up to 26 bar, a medium-BMEP combustion layout was applied representing continuous rating applications. For higher BMEP ratings, representative of applications such as standby power generation or marine fast vessels, a high-BMEP combustion layout was applied, thereby enabling better utilisation of the PFP capability of the engine for highest efficiency.

Constant power trend lines are displayed that clearly demonstrate the potential efficiency benefit from achieving a given rated power through increased BMEP at a reduced rated speed. The high BMEP capability is an enabler for such rated speed reduction at a still competitive power density.

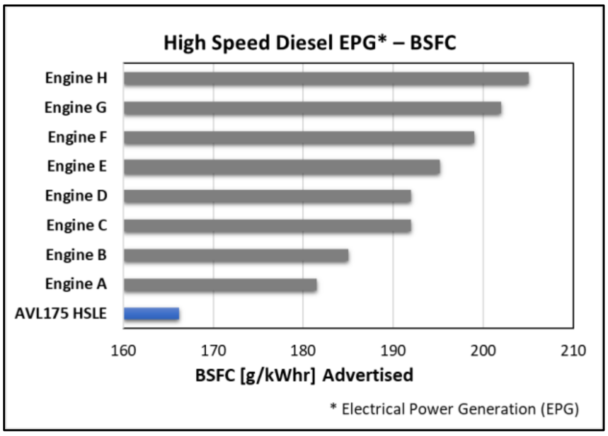

Figure 22: Comparision of High Speed BSFC advertised

To evaluate potential reduction in GHG emissions a benchmark comparison of competitor engines is shown in Figure 22 for eletrical power generation ratings. Although the comparison group contains multiple rated BMEPs, the high-efficiency AVL175 shows significant advantage.

Figure 23 shows a comparison of rated power CO2 emissions vs engine-out NOx emissions at 26 bar BMEP 1500rpm. The lower trade-off curve is the AVL175 MCE-equivalent, the upper curve is a benchmark current MCE-equivalent engine. A reduction of 9-18% at equivalent NOx emissions can be realised.

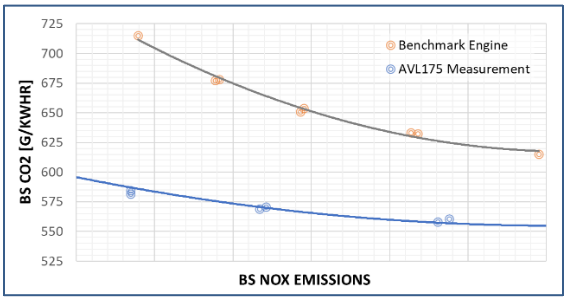

Figure 23: 1500rpm 26 bar BMEP BSCO2 vs. BSNOx Emissions trade-off Comparison

7 TEST RESULTS GAS

For the high BMEP gas combustion a gas-fed prechamber with spark ignition concept was selected. Gaseous fuel was administered in a pre-mixed condition by gas admission valve located in the intake plenum. A separate gas supply to a gas-fed spark-ignited pre-chamber provided high energy ignition to the main combustion chamber.

During a front-loaded design and development process, thermodynamics studies were performed to investigate the best combination of IVC, Compression Ratio, combustion timing and excess air ratio. All investigations were considering emissions fulfillment and knocking resistance.

CFD investigations were performed to evaluate a number of pre-chamber designs, with consideration of multiple parameters within the prechamber e.g. swirl, tumble, TKE near the spark plug, mixture lambda, homogeneity levels in various regions of the pre-chamber, and combustion stability indication such as EGR levels in various PC regions. A selected few pre-chambers were prepared for SCE evaluation.

Testing on the SCE was performed initially up to 32.5bar BMEP at 1500rpm with an engine-out emissions cap of 500mg/Nm³ NOx at 5% O2.

The results of the testing are summarised in Figure 24. Brake thermal efficiencies up to 32.5 bar BMEP exceeded 50%.

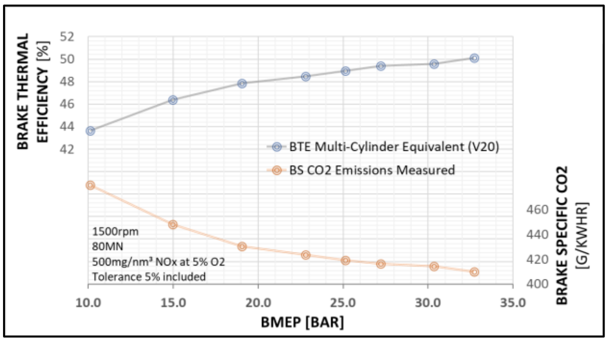

Figure 24: Measured BTE and CO2 Emissions PCSI Gas

Results also indicated stable combustion with acceptable PFP COV. Testing was further performed at reduced MN gas and increased intake manifold temperatures to establish the combustion system sensitivity. Additionally, performance and emissions tests were performed at BMEP levels higher than 32.5 bar to investigate further the engine's capability.

Further investigation work is planned with regard to combustion optimisation and documentation of additional pre-chamber design variants, based on promising CFD results.

8 TEST RESULTS H2 COMBUSTION

The AVL175 SCE was configured for low pressure H_2 gas admission upstream of the intake port. Ignition approach was selected as open chamber spark ignition (OCSI) to demonstrate a simplified engine configuration potentially representative of an OCSI gas engine conversion.

With OCSI port admission H_2 combustion up to 18 bar BMEP was achieved with stable combustion.

Figure 25 shows a comparison of rates of heat release (ROHR) for three combustion and fueling concepts at similar BMEP levels. The combustion speeds of the diesel and PCSI gas are significantly faster in comparison with the OCSI H_2 combustion. Due in part to the quiescent in-cylinder flow design which is preferable for high efficiency with strong ignition sources (diesel and PCSI).

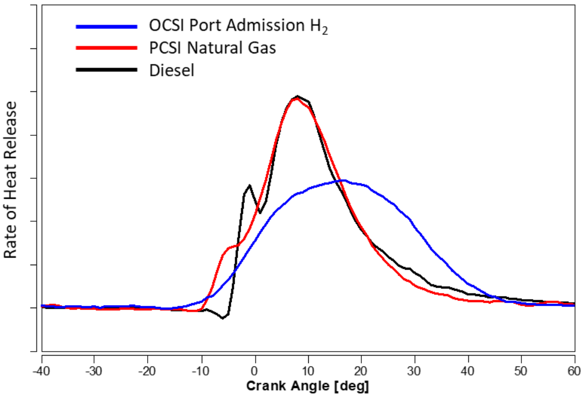

Figure 25: Rate of Heat Release Comparison

H_2 combustion speed could be increased further by inducing air turbulence, introducing squish, improving the ignition strength by introduction of a gas-fed prechamber or by direct injection of H_2 into the combustion chamber.

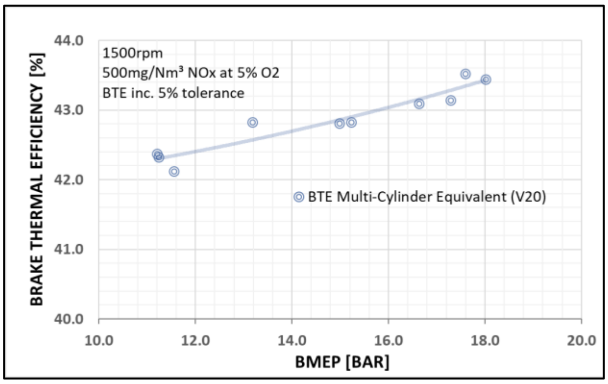

Figure 26: Measured BTE OCSI H_2

The resulting BTE values of the H_2 operation, summarised in Figure 26, while comparable to similar OCSI gas engines, is notably lower than for the PCSI gas and Diesel configuration shown.

CO_2 emissions were measured and were, as expected, negligible with any trace emissions accountable to low rates of lubricating oil consumption.

9 CONCLUSIONS

The key objective for the design of a new high-speed engine design with high PFP and BMEP capability, was to investigate potential efficiency improvements that could transfer into potential CO2 emissions benefits on conventionally fueled high speed large engines.

The front-loaded design and analysis procedures were verified on a single cylinder engine and measured efficiencies met and even exceeded the original goals.

Hydrogen fuel testing indicated promising capabilities of a low-pressure gas admission, open-chamber spark ignited layout and is indicative of possible retrofit solutions for GHG emissions reduction. Further optimisation of the H_2 combustion concept on the AVL175 engine is expected to improve further the combustion efficiency and other performance parameters.

The engine is also intended to be an efficient platform with planned further investigations into low carbon fuel combustion concepts.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

BSFC:	Brake Specific Fuel Consumption
BMEP:	Brake Mean Effective Pressure
BTE:	Brake Thermal Efficiency
CO_2:	Carbon Dioxide
CGI:	Compacted Graphite Iron
CFD:	Computational Fluid Dynamics
COV:	Coefficient of Variance
CR:	Compression Ratio
CRA:	Crank Angle
EHD:	Elasto Hydro Dynamic
EGR:	Exhaust Gas Recirculation
FE:	Finite Element
FMEP:	Frictional Mean Effective Pressure
GHG:	Greenhouse Gas (emissions)
GJL:	Gusseisen mit Lamellengraphit (Grey cast iron)
GJV:	Gusseisen mit Vermiculargraphit (Compacted Graphite Iron)
H_2:	Hydrogen
IVC:	Intake Valve Closing
MCE:	Multi Cylinder Engine
MPS:	Mean Piston Speed
NOx	Nitrogen Oxides
OCSI:	Open-Chamber Spark-Ignited
OEM	Original Equipment Manufacturer
PCU:	Power Cylinder Unit
PCSI:	Pre-Chamber Spark-Ignited
PFP:	Peak Firing Pressure
ROHR:	Rate of Heat Release
RPM	Revolutions per minute
SCE:	Single Cylinder Engine
SSTC:	Single Stage Turbocharging
TBO:	Time Between Overhaul
TKE:	Turbulent Kinetic Energy
TSTC:	Two Stage Turbocharging

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