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3D Printed Piston for Heavy-Duty Diesel Engines

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ABSTRACT

3D printing is a rapidly evolving technique for alternative piston manufacturing that offers the ability to realize complex combustion bowl geometry, robust structure and advanced cooling channel geometries while delivering precise tolerance and mass control. IAV has designed, analyzed, optimized and produced 3D printed pistons for heavy-duty diesel engines. The key features include an innovative form of combustion bowl, 300 bar peak cylinder pressure capability and advanced cooling channels in a mass neutral to less capable design. During 2018, these pistons will undergo fired engine testing.

INTRODUCTION

As an interface between the combustion process and engine mechanical sub-systems, very high demands are placed on the pistons of a heavy-duty diesel engine. The combustion chamber design can influence the spray penetration length, air-fuel mixing, combustion behavior and consequently efficiency and emission formation. The trend of increasing combustion pressures continues to make the structural considerations even more demanding for large-bore heavy-duty engines. As a result, novel techniques are well appreciated to develop robust piston structures while keeping mass and compression ratio in check. For a given bore/stroke and combustion system, piston mass drives other engine design considerations that have a major influence on engine speed (rated power), overall engine size and mass, including crankshaft counterweight dimensioning, crankcase deck height (engine height), connecting rod small end bearing system, etc. The cooling features of the piston support many functions, several of which are even more critical with advanced combustion systems: robust control of bowl surface temperature to support proper mixture preparation, dimensional stability of the piston to manage friction, blow-by and peak oil temperature to minimize oil oxidation and deposit formation. Reduction or even omission of piston oil jet cooling can enhance the thermal efficiency of the engine and increase the oil service interval.

On the other hand, freight transport continues to increase and the road remains the main carrier. For example: within the three million registered commercial vehicles in Germany, 95% are powered by diesel engines due to its unbeatable fuel economy. Thus, commercial vehicle diesel engines have a significant impact on air quality and legislators are increasingly forced to limit the (partly toxic) pollutants. In particular, the reduction of nitrogen oxide emissions (NOx) with the slight increase in soot and fuel consumption is the current challenge for heavy-duty diesel engine development.

The well-known trade-offs between fuel consumption / NOx and NOx / soot request even more complex technical solutions to reach an overall optimum. Current emission concepts for Euro VI and US EPA 2010 rely on the use of highly efficient SCR catalysts and low exhaust gas recirculation rate (EGR) in order to reduce the NOx with slight a fuel consumption increase. For CARB 2024 and beyond, the high-efficiency SCR catalysts are an important part, but higher EGR rates should be considered to realize ultra-low NOx concepts. Due to the limited oxygen content in the combustion chamber, an increase in EGR is accompanied by an increase in soot formation and lower soot oxidation. This can be counteracted by improved mixture formation, e.g. increasing injection pressure or redesign of the piston bowl geometry. Increasing injection pressure up to 3500 bar is under investigation at IAV but not in the scope of this article. It is focused on innovative piston bowl design using higher degree of design freedom using 3D printing technology.

This technology makes it possible to create pistons not only from well-known standard metal alloys (like stainless or tool steel, nickel and cobalt alloys), but also from a wide range of new metal matrix composites based on e.g. aluminum, steel or titanium.

OPPORTUNITIES WITH 3D PRINTING

3D printing or additive manufacturing is a collective name for a number of technologies, which vary in their method of layer manufacturing. Among these technologies, which were classified by ASTM in 2010, are Binder Jetting, Material Extrusion and Powder Bed Fusion.

One type of the powder bed fusion is the Selective Laser Melting (SLM), also referred to as Direct Metal Laser Sintering (DMLS) process. During this process, a thin layer of powder material is spread over the build platform using a roller. A laser melts the powder to form the required cross sections while at the same time fusing them to the previous layers. The process takes place in an argon or nitrogen environment depending on the printed alloy. The building speed on recent SLM printers is about 1 to 2 pounds per day. Apart from this moderate printing speed, the SLM process is relatively accurate (tolerances down to approx. ±0.1 mm), guarantees a high material density (approximately 99.5%) and leads to low content of oxides and nonmetallic inclusions.

Pistons produced by the SLM process do not need any draft angles and may evince undercuts. On the other hand, the angle between each part surface and the (vertical) build direction should not exceed 45° to ensure sufficient support for the melt pool. Otherwise, support structures are required. The powder has to be removed completely from all channels and cavities. Therefore, these areas need at least one small opening.

The usual SLM steel alloys are different from quenched and tempered forging steels in terms of Young’s modulus and thermal conductivity. Furthermore, the piston gets orthotropic material properties because of the SLM printing process.

To use the full lightweight construction and robustness potential of 3D printed pistons, a dedicated design approach is required, considering all the above mentioned specifics. The use of a framework or honeycomb structure instead of thick solid walls increases the bending stiffness of these innovative pistons in comparison to forged ones, without increasing their weight. The local thickness of the ribs can be adapted to the load they actually have to transfer. The thickness of the ribs can be reduced down to about 1.0 mm for steel parts.

For highly loaded pistons of gasoline and diesel engines, a number of different materials are available for 3D printing. Among them, there are materials, which can be casted or forged as well. These materials include high strength tool steels (e.g. 18% Ni Maraging 300 for piston temperatures up to 1000 °F), nickel alloys (e.g. IN718 for temperatures up to 1300 °F) and cobalt super-alloys (e.g. ASTM F1537 Alloy 2 for temperatures up to 1900 °F). On the other hand, a complete new material family of metal matrix composites (MMC) reinforced with ceramic particles is available. These materials, which usually cannot be forged, combine the toughness and ductility of metals with the hardness, strength, stiffness and wear resistance of ceramics. Even at high temperatures, the enhanced strength is preserved. A number of aluminum based MMCs are available for printing of gasoline or lower loaded Diesel pistons. New MMCs are in development, e.g. with steel, titanium or nickel matrices, and offer the opportunity to improve the load capability and robustness of heavy-duty pistons in the near future.

ADVANCED HEAVY-DUTY PISTON DESIGN CONCEPT OF IAV

In order to take full advantage of the design freedom and new material selection provided by 3D printing and to investigate the resulting potential for combustion process improvement, IAV has carried out an in-house advanced piston design study for a heavy-duty engine. The resulting design was manufactured in 3D printing at a manufacturing partner.

A main target of this design study was to realize an innovative piston bowl shape (see figure 1) which enables and improves mixture formation by increased penetration depth of the fuel jet and free jet length. Secondly, a completely new piston design including a special rib structure and cooling channels has been developed to demonstrate the new design possibilities for higher stiffness, which are provided by 3D printing. An approximately 130 mm piston diameter was investigated for this study.

Figure 1: Innovative piston bowl design for heavy-duty engine by IAV

Piston Bowl Geometry

The idea of the advanced piston bowl design is to align the bowl layout along each fuel jet. Consequently, the piston bowl is not rotationally symmetric and forms something like a housing around the fuel jet. Figure 2 shows the comparison between a conventional piston bowl design and the advanced piston of IAV. A cross section view along the jet axis is shown in figure 3. With the advanced piston bowl layout, the free spray penetration length is increased by 25% compared to conventional designs. In addition, the bowl contour has been adapted to improve the squish flow and mixture formation.

The advanced piston bowl shape is able to work with a relatively low swirl ratio. Since both pistons should be investigated without any modification on the cylinder head, the target swirl at intake valve closing (IVC) will be the same for both pistons.

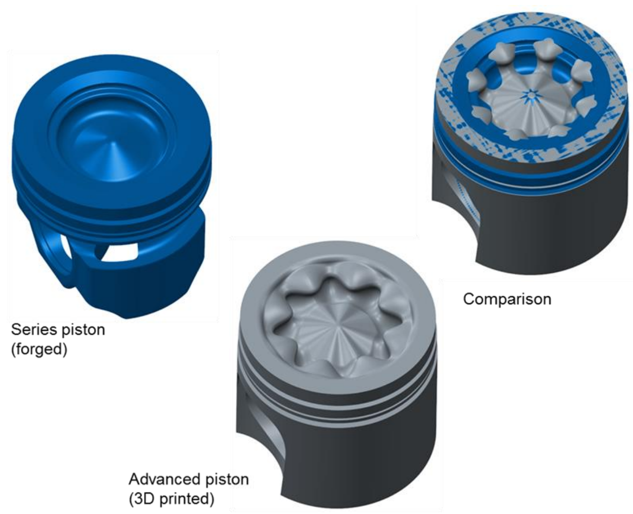


Figure 2: Comparison of a conventional and the advanced piston of IAV

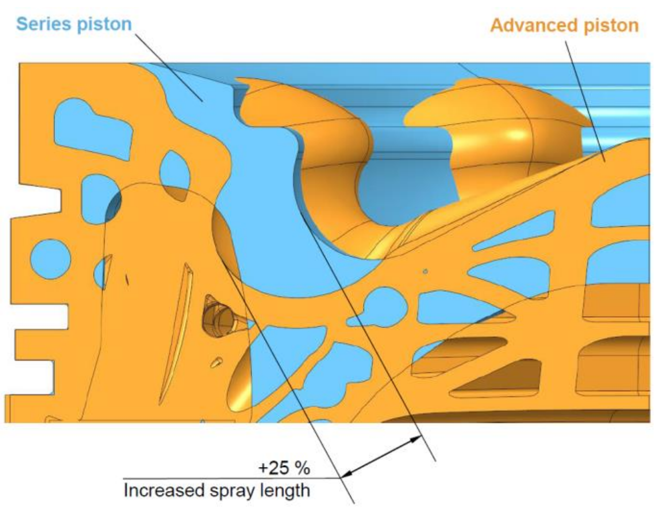


Figure 3: Longitudinal section through the conventional (blue) and advanced piston bowl (orange)

The 3D-CFD analysis of fuel injection, mixture formation, combustion, pollutant formation has been carried out with sector meshes by using STAR-CD in combination with IAV in-house tools (e.g. IAV KoMu [1]). Segment models contain only one injector spray plume with their surrounding gas volume. The cylinder head and the valve faces are modeled by a simple disk and the piston is simplified by omitting valve pockets. The thereby neglected volume is added in the top land region of the piston to conserve the compression ratio. The gas phase is divided into finite volume elements in which the Reynolds Averaged Navier Stokes equations (RANS) are solved. The resulting numerical grid for the conventional and the advanced combustion chamber is illustrated in figure 4.

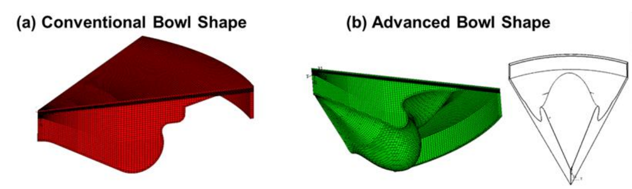


Figure 4: Numerical grids in top dead center position for 3D-CFD analysis

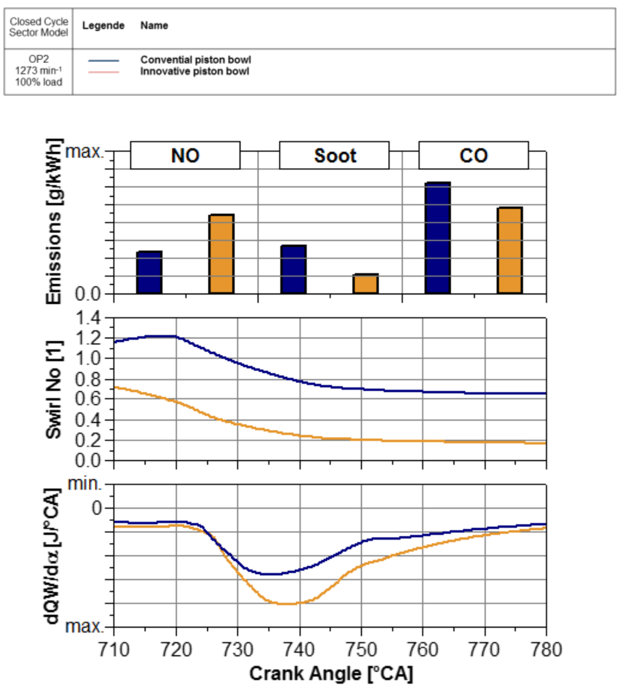
The fuel injection is described by the Lagrangian multiphase method by using sub-models for nozzle flow, spray atomization, break-up and spray-wall-interaction. As combustion model, the ECFM-3Z model is used in combination with Section Method soot model and Zeldovich nitrogen oxide model.

For the development of the advanced piston bowl design, the parameters and operating conditions of a single cylinder engine were used, see table 1. All investigations have been carried out by using the same injection rate and timing, same initial conditions (including swirl ratio) and same wall temperature.

		Operating point 1 (OP1)	Operating point 2 (OP2)
Engine Speed	RPM	1273	1273
Engine Load	%	25	100
Bore / Stroke	mm	128 / 157	
Cylinder Displacement	L	2.02	
Number of Nozzle Holes		8	

Table 1: Engine main dimensions and operating conditions

The simulation results for OP2 are shown in figure 5. As mentioned earlier, the cylinder head and therefore the swirl ratio at IVC (Intake Valve Closing) has to be the same (=1.0). The swirl at SOI (Start of Injection) or TDC (Top Dead Center) differs anyway. With the conventional bowl shape with smaller bowl diameter, the swirl ratio increases from 1.0 at IVC to approx. 1.2 at SOI due to the conversion of angular momentum. Since the advanced piston bowl shape is not rotationally symmetric, the swirl flow motion is dissipated by this contour. Therefore, the swirl ratio is reduced from IVC to SOI despite the same effect as for the conventional bowl is also present. This is also visible in a reduced deflection of the fuel jet during the combustion (refer to figure 6).



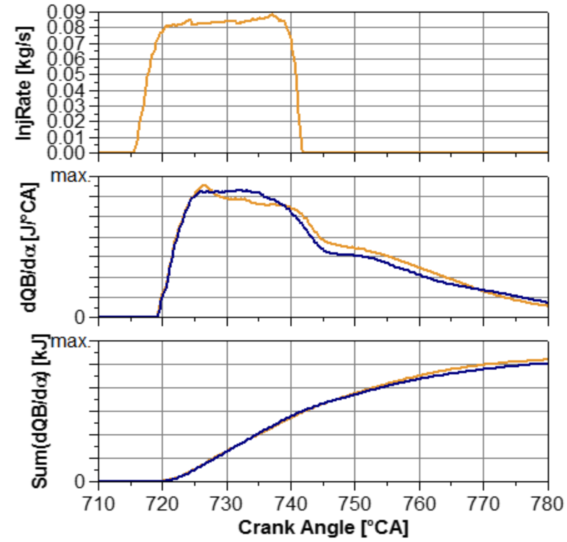


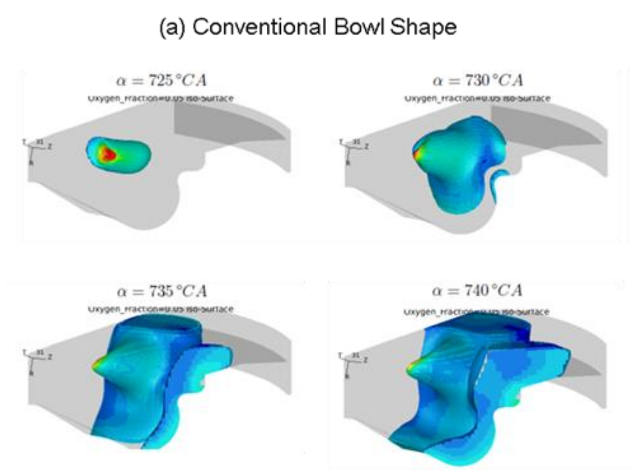
Figure 5: Injection rate as input and heat release results from 3D-CFD analysis at operating point 2

Despite of the different swirl ratios at SOI and TDC, the start of combustion and the premixed part of combustion is similar for the conventional and advanced piston design. At approx. 725° Crank Angle (CA) the diffusive part of combustion begins and differences are visible in burn rate. The advanced piston bowl shows a slightly lower level of heat release during this stage of combustion than the conventional bowl. One of the main reasons for this behavior is the different swirl level. Another reason is the earlier spray-wall-contact at the piston bowl with the conventional bowl shape as shown in figure 6. Consequently, the surface area of the reaction zone increases and more fuel can be oxidized at the same time. However, at the post-oxidation part of combustion (after 740°CA), the burn rate of the advanced bowl shape is higher than the conventional one. This leads to a higher rate of CO and soot oxidation and finally less specific CO and soot emissions. This is caused by the fact, that the conventional bowl needs more kinetic energy coming from fuel injection to realize the back flow into the bowl. Due to the increased free spray penetration length of advanced bowl shape, the post combustion works better even if the injection has been finished. Furthermore, less interaction between neighboring jets is visible at 740 °CA, which improves the air utilization.

Despite the higher released heat, the advanced bowl has a comparable thermal efficiency. One reason for this is the slightly later center of heat release (COHR). This would not be the case if COHR was kept constant by optimized calibration of SOI. The second reason is the increased wall heat losses due to increased surface area (+12%) of the advanced bowl shape.

As mentioned, this analysis was carried out for advanced piston with same wall temperatures as the conventional piston. Therefore, the potential of improved piston cooling/insulation, which was not assessed and considered in the current simulation, will increase the thermodynamic benefits. Besides that, there is further optimization potential to optimize the piston bowl design, especially in combination with ultra-high injection pressure (3500 bar) to best use the benefits from the increased penetration length.

All further potential regarding improved piston cooling/insulation and bowl design for ultra-high injection pressure are currently under development by IAV.



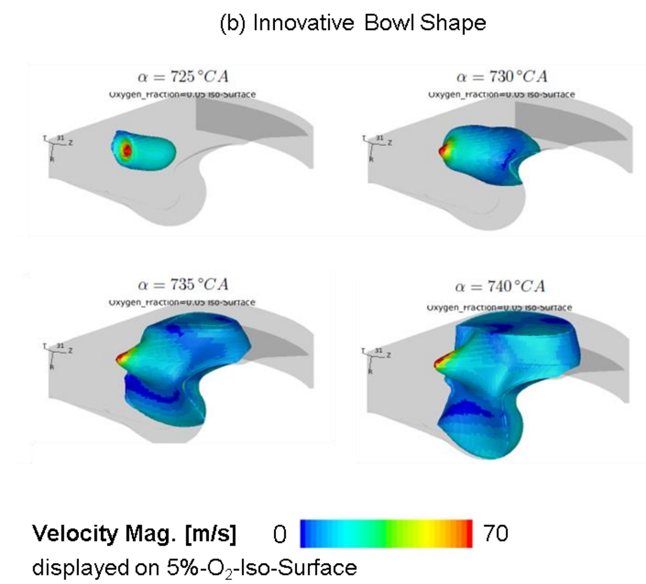


Figure 6: Visualization of combustion progress (result of 3D-CFD analysis)

Mechanical Design

As mentioned before, with 3D printing, it is possible to design and manufacture pistons with complex mechanical structure and high production accuracy.

In heavy-duty piston design study of IAV, a complex two-stage cooling concept was implemented (figure 7). The first stage consists of partially sodium-filled channels. As known from sodium filled exhaust valves, sodium is an excellent heat conductor and can handle very high wall temperatures (> 1800 °F) without degradation or pressure increase. One channel system (figure 7 in red color) is dedicated for the cooling of sensitive zones of the piston bowl. Tolerable surface temperatures are mainly depending from the oxidation resistance and high-temperature strength of the piston material. For surface temperatures above 930°F, a rapid oxidation of forged AISI 4140 parts will start. 3D printed pistons from ASTM F1537 Alloy 2 can withstand temperatures even up to 1900°F, which creates a huge potential for the power density and thermal efficiency of heavy-duty engines. Another channel system primarily serves the cooling of the first piston ring groove (figure 7 in orange color). When the ring groove temperature rises above 510°F, the risk of ring sticking increases dramatically. Ring sticking can not only amplify the oil consumption and blow-by rates, but also cause a total damage of the engine. The acceptable limit for the first ring groove temperature is mainly linked with the oil degrading and is independent from the piston material. Both sodium filled channel systems are not connected to each other. This avoids a direct heat transfer from the bowl surface to the ring groove and prevents the latter from overheating.

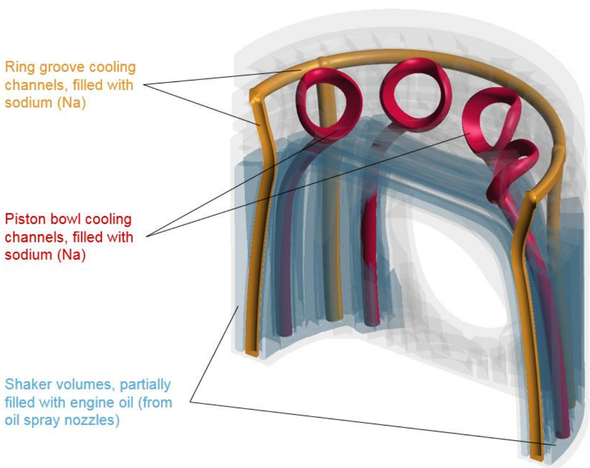


Figure 7: Two-stage cooling concept of the design study

In the second stage, the engine oil in the shaker volumes takes over the heat from the sodium cooling channels (1st stage) (figure 7 in blue color). The sodium cooling channels lead from the hot regions to the oil shaker volumes in the piston skirt where a ribbing significantly increases the surface area of the cooling channels. This reduces the surface temperature and thus the risk of degrading of the engine oil. The two shaker volumes are connected to each other via transverse channels above the piston pin and are supplied with cooling oil on the anti-thrust side by an oil spray nozzle.

The first experiments with sodium-filled pistons were carried out about 80 years ago on aircraft engines. However, the heat from exceedingly hot zones was forwarded only to the colder piston skirt and from here to the cylinder liner. An additional splashing with cooling oil was not foreseen, so the amount of dissipated heat remained limited. Only the consistent combination of sodium cooling systems with oil shaker cooling, implemented in the study, meets the demands of the thermo-management for high-performance steel pistons.

The hot piston crown and the oil-filled channels are heat insulated by evacuated cavities. The cavities are part of the framework structure and their openings are airtight welded by electron-beam after removing the 3D printing powder. The cavities prevent splash oil from coming in contact with piston surfaces hotter than 660 °F.

The rib structures in the piston crown and the piston skirts (figure 8) reduce the weight of the part and ensuring its robustness. In addition, the heat flux between the crown surface and the pin bore is reduced by the halved thermal conductivity of 18% Ni Maraging 300 in comparison to AISI4140 material and because of the smaller cross-sectional area of the ribbed structure.

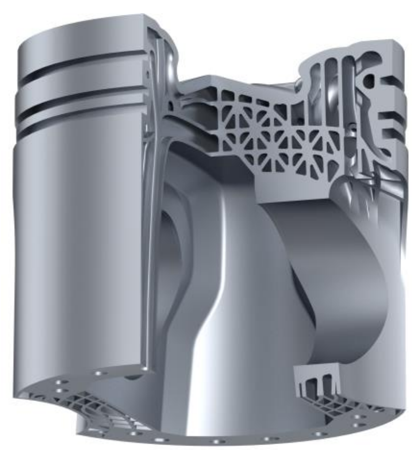


Figure 8: rib structure design of IAV

After the design and calculation work are finished, the 3D model of the piston is ready for printing. The next production step is to remove powder from all cavities, channels and then eliminate the printing supports. Usually the printed parts will be heat treated and then machined. Steel pistons undergo a phosphating. Finally, the piston skirts will be coated with anti-friction coatings.

SUMMARY AND OUTLOOK

As demonstrated by the IAV heavy-duty piston design study, 3D printing enables a completely new approach for piston design. Optimized designs of piston bowl shapes, which are no longer rotationally symmetrical and can have undercuts, are possible with this new technology and lead to significant improvement of air-fuel mixing and combustion process. Such bowl shapes cannot be manufactured with classic technologies like casting or forging. For combustion performance and strength, optimal cooling of the piston bowl was attained through the design of a novel channel system, which is partially filled with sodium. Another channel system primarily serves the cooling of the first piston ring and is not connected to the other system. This avoids a direct heat transfer between the bowl and the ring groove. A second cooling stage transports the heat to the engine oil.

Using IAV’s rib structure for the lower part of the piston ensures a high stiffness in combination with low weight. This opens the way for future applications with high power density and high peak firing pressure.

In 2018, 3D printed pistons are still too expensive for a mass production of high production volume engines, but IAV expects a continuous decrease of manufacturing prices in the future. For small production volumes or special applications, 3D printed pistons can be a highly attractive option.

In addition, 3D printed pistons are excellent development tools for combustion development, e.g. in single cylinder engines, like the IAV Single Cylinder Engine. After implementing a manufacturing process for a specific piston, IAV expects 2 weeks lead time for the manufacturing. This increases significantly the development speed of new pistons bowl shapes, cooling concepts or materials and ensures a fast matching of simulation and testing results.

IAV is working continuously on new variants of heavy-duty diesel engine pistons for high power density. In parallel, other applications for 3D printing, like valve train parts, turbine housings and cylinder heads for single cylinder are also under detailed investigations.

REFERENCES

[1] C. Schramm, “CFD simulation for combustion process optimization at a commercial vehicle”, Diploma Thesis University of Applied Science Zwickau; 2009.