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Studying a construction of pistons for the aircraft CI engine

This paper examines the selected constructions of piston for aircraft CI engines and discusses tendencies in a development of piston designs. The paper addresses the question of using new materials and coatings to improve quality of pistons and the study of heat transfer and methods to absorb heat from a piston by means of cooling ducts. The selected materials were examined in terms of their advantages and drawbacks. The paper discusses different shapes of piston heads and their impact on combustion as well as indicates other factors behind parameters of combustion and toxic emission like injector shape types, lubrication types and clearances in the combustion chamber.

Key words: *aircraft engine, piston, CI engine, opposed-piston engine, designing pistons*

1. Introduction

Compression-ignition engines are not common aircraft drive units but for many years it has been often successfully attempted to install them in the aircraft. Recently, some new constructions of pistons for compression ignition engines have been launched onto the market. In 2014, the first steel pistons for an automotive passenger CI application began to be sold [22]. Computational fluid dynamics enables heat transfer and combustion of a charge to be optimized. These are the tools that were not available for constructors in the last century, so engine manufacturers take older proven designs to improve them. Civil light aviation also uses aircraft with engines previously verified in automotive applications and which can become attractive solutions in civil aviation satisfy as they satisfy very demanding toxic emission standards and show low fuel consumption. The paper investigates piston designs dedicated to diesel engines. Small aircraft engines are very often based on verified automotive solutions so the focus is put on advances in automotive engines of a potential aviation application.

This paper follows an approach of critical analysis and investigates the known aviation and automotive piston constructions. Investigating non-scientific and commercial materials is purposeful to achieve a more comprehensive state-of-the-art about modern constructions of pistons as automotive applications to be successfully transferred to aviation.

2. Aircraft CI engines

When aircraft CI engines began to be developed in the 1940s, there were first turbojet and turboprop engines that successfully satisfied the needs of aviation at that time. Progress in automotive CI engines was reflected in aircraft engines so diesel aircraft engines were rediscovered in the 21st century.

Balicki et al. [1] claim that piston engines now frequently used in light and ultralight aviation by aeroclubs and for business, economic, rescue and recreation purposes technically represent a pre-war theory of operation, designing and technology of production, especially if regarded the progress in automotive engines. Low pressure injection engines are rare and frequently carburetors of a quite primitive construction are used. Ecological standards and climate change can significantly stimulate the progress in developing aircraft piston engines, even by transferring to them the achievements in automotive applications. Regardless of this, it is considered to introduce CI engines capable of running on one type of fuel.

Thielert Aircraft Engine GmbH, until its insolvency announced in 2008, was a recognized manufacturer of aircraft engines, including the Centurion range of aircraft CI engines. In 2013, the company was taken over by Continental Motors, Inc., owned in majority by China's AVIC International and renamed Technify Motors GmbH. Thielert's engines were mainly based on automotive turbo-diesel engines [14], however, for example, 180 original parts were designed for the Centurion 1.7, an inline-four engine [4]. The Centurion 1.7 was installed in the Piper, Cessna 172 and Diamond DA42 "Twin Star". The latter airplane, when the production of the Centurion 1.7 was suspended in 2009, was adapted by its manufacturer, Diamond Aircraft Industries, to the Lycoming gasoline engine and the turbodiesel Austro Engine E4 (Austro AE300) by Austro Engine GmbH. The bankruptcy of Thielert Aircraft Engine GmbH largely impacted the sales of the DA42 which since its launch onto the market in 2004, constituted 80% of the sales of 2-piston engine aircraft [15].

In 2009, the Italian manufacturer of light aircraft presented the Gemini100, a British diesel engine by Power Plant Developments, installed in the Tecnam P92. The Gemini100 is a compact opposed-piston engine of similar parameters to petrol engines (Gemini100: capacity – 1.6 l, power – 100 KM, weight – 70 kg, fuel consumption – 11–12 l of karosene/1h of flight; Rotax 912: 80-100 KM, 60 kg, 5000-5500 rpm, fuel consumption 15 l of petrol/1h of flight). The Gemini100 has been modified since 2006, and in 2015, it was announced that the research on this engine had been continued [18].

The Diesel V-8 Graflight by Engineered Propulsion Systems is another engine installed in a single-engine piston aircraft, the Cirrus SR22. This aircraft typically operates on the Continental IO-550-N 310 HP. In 2014, there was its first test flight. Manufacturer's representatives claimed that its time between overhaul (TBO) had been successfully extended up to 3000 hours and the engine would soon undergo certification procedures [17].

Fig. 1. Gemini100 engine [16]

The opposed-piston engine is a technologically interesting aircraft CI engine. The first opposed-piston engine was built in 1890, and since then have been used in ground, marine and aviation applications. Unlike the four-stroke engine, this type of engine doesn't need the head and valves which are considered to be the most expensive parts of standard engines. One of the most significant opposed-piston engines is the Junkers Jumo, designed and developed by Professor Hugo Junkers for the German army and civil aviation and manufactured between 1930 and 1945. In those days, the Junkers 205 and 207 showed unusual performance [13]. Other well-known opposed-piston engines include: Doxford (1920-1990), used in a wide range of ships, Kharkov 6TD (1932-current), used in Russian tanks, Fairbanks Morse 38D81/8 (1934-current), used in United States submarines, small marine freighters and trains, Rootes TS3 engine (1954-1972), used in the United Kingdom Commer truck, Napier Deltic engine (1954-current), used in high-speed trains and naval fast patrol boats, Rolls Royce K60 (1955-current), used in military applications, Leyland L60 (1960s-1995), used in the United Kingdom, produced Chieftain Battle Tank [13].

Junkers was working for 20 years to build an aircraft diesel engine and the Junkers Jumo 205 showed the best results and started the entire engine family. Figure 2 shows its design [24].

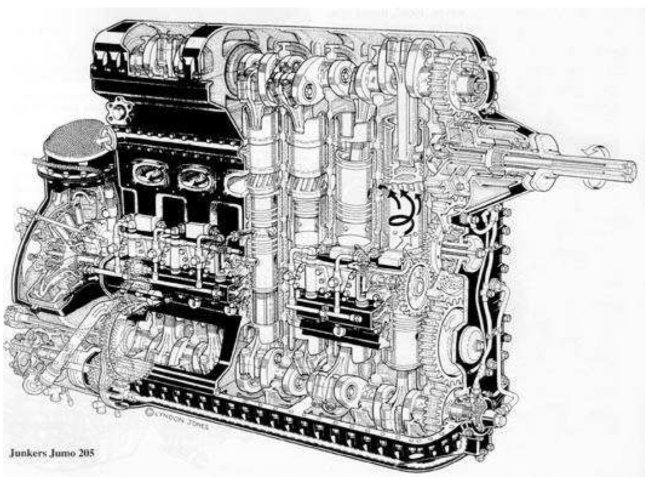


Fig. 2. Junkers Jumo 205 engine [24]

Despite their many advantages, opposed-piston engines had one disadvantage, i.e. high toxic emissions which suspended their progress for many years. Since the early 1980s, emission standards for all motor vehicles have eliminated all of the engines available at that time, mainly for their poor fuel injection system and a non-optimized geometry of their combustion chamber. Technological progress and up-to-date design methods have enabled this type of engine to be relaunched onto the market. With computational fluid dynamics and simulation software, these engines have been revived as a viable alternative and a product to fill a market gap [13].

In 2013, Achates Power was granted nearly U.S. $ 5 million from the United States Army to improve and develop a new engine based on the Junkers Jumo 205 design [2]. Actually, this engine can be further developed with today's advanced technologies.

3. Trends in designing pistons for CI engines

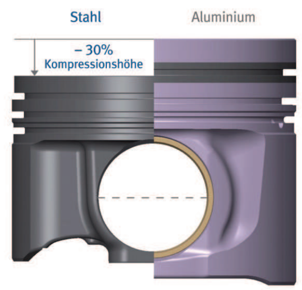
The piston in the compression ignition engine has varied tasks. It transmits the forces from and to an air-fuel mixture, shapes and seals the combustion chamber and releases heat generated by combustion. For many years, pistons have been typically made of aluminum alloys. In time, however, engines have been expected to be more efficient so their designs have had to be improved. Actually, the entire engine has been modified but this paper focuses on pistons and how they impact toxic emissions emitted by the CI engine. There are many methods to satisfy the increasingly strict toxic emission standards but the most frequently regarded solutions to be applied in pistons focused on changing their design, modifying shapes of the combustion chamber, using innovative nano-coatings or finding a more appropriate material or manufacturing technology.

David Adams, specialist from Ford's Dunton engine R&D centre in the United Kingdom, claims that already in 2012, there were strong tendencies to use steel pistons in diesel engines. Such a change, he says, is probably the most significant innovation in the use of new materials for automotive pistons. There have been the attempts to optimize aluminum-silicon alloy pistons with the use of additional alloying elements that improve the microstructure, stability and strength of the casting. However, the density of the material prevented from achieving lighter pistons, so the focus was put to find stronger materials to manufacture thinner sections and create better casting technology. Graphite coatings, almost standard for all types of pistons, have managed to reduce friction on the skirt and, to some extent, wear. Composite carbon-nanotube coatings, so far used on piston rings, are now also on the piston [12].

AVL's R&D work on pistons has been also focused on using steel for pistons, especially for high-power passenger car diesel engines where the maximum cylinder pressure reaches 200-220 MPa, whereas the limit for aluminum pistons is about 210 MPa. AVL has partially collaborated with suppliers to develop a steel piston as heavy as an aluminum one. They succeeded by special micro-friction welding processes in which the piston head and shaft were welded together under pressure by micro movement. AVL claims that welding two elements is more cost effective than a complex casting. This type of technology is used for heavy-duty pistons [12].

4. Materials for pistons

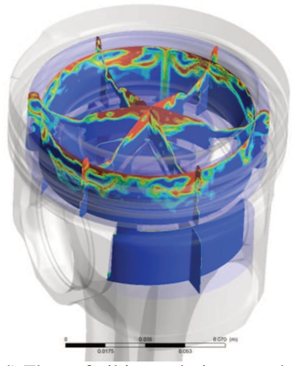
Piston's tasks and loads applied to the piston – varied-load strength, correct thermal conductivity, rapid temperature changes, a correctly low friction coefficient – are the factors behind the choice of materials for the piston. If the piston is to be lightweight, low density materials are preferred. The most common material for pistons in most internal combustion engines is aluminum alloy which is preferred for its low weight, low mass production costs and strength under conditions that occur in the cylinder. Recently, CI engines have been more loaded so aluminum pistons frequently need to operate on the verge of their permissible loads. Therefore, designers have turned to steel which more high-temperature resistant and stronger. Rheinmetall Automotive Company reports that since 2014, the German company, Kolbenschmidt, has been the world's first supplier of steel pistons for passenger car diesel engines [22] and steel pistons with aluminum piston heads are capable of reducing fuel consumption and engine weight [21]. Properties of steel and its better than aluminum stability enable pistons to be smaller though stronger to higher loads. In addition, frictional forces are weaker than those in aluminum pistons. Better combustion conditions result not only from a changed material for the piston but also from the innovative patented LiteKS piston design that is able to reduce weight but not deteriorate strength as well as the use of nanomaterials (NanofriKS coating on the shaft).



a) Geometrical comparison of steel and aluminum pistons

b) Steel piston dedicated to CI engine vehicles

c) Steel piston dedicated to CI engine vehicles - cross section



d) Flow of oil in steel piston cooling channels

Fig. 3. Steel piston dedicated to diesel engines [20]

Rheinmetall Automotive AG's steel pistons are dedicated to compression-ignition engines in which cylinder pressure is more than 200 MPa and power higher than 100 kW/dm^3. Their weight is similar to that of aluminum pistons, and their smaller dimensions can reduce lateral and frictional forces and reduce fuel consumption by 2-3%. For their special design, they can be installed in the engine with a reduced core height**.** The optimized configuration of piston cooling and adapting combustion parameters can compensate for a relatively poor thermal conductivity of steel compared to that of aluminum and related higher temperatures on the surface of the combustion chamber. A large closed cooling channel is directly next to the area of critical temperatures so optimal cooling is provided. Favorable temperature distribution that occurs in the area around the piston reduces both carbonization of the ring groove and piston ring's wear. This patented design is a single-piece forged piston, which can guarantee a negligibly deformed ring groove [19].

Figure 4 shows the temperature distribution for two pistons made of different materials, operating under the same conditions. The cooling channel in the steel piston protects the piston ring by lowering its temperature even by 50°C compared to that of the aluminum piston. The highest temperature is in the upper and lower sections of the combustion chamber but it is higher by 30°C than in the aluminum piston [8].

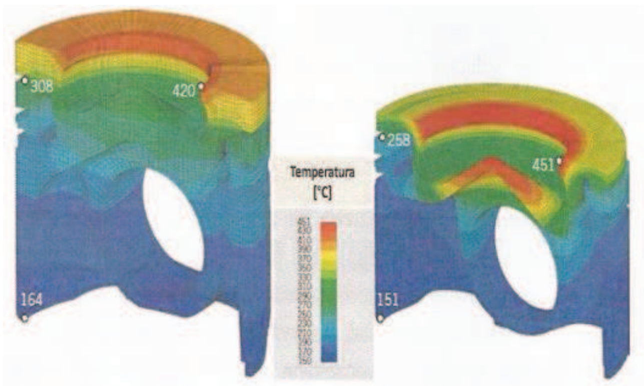


Fig . 4. Distributions of temperature in aluminum and steel pistons [8]

Figure 5 shows the distribution of safety factor, calculated from the load applied to pistons as a function of temperature. The stress in the aluminum piston is similar to the permissible stress level, whereas in the steel piston, there is a certain stress spare so there is no risk of surface cracks. The boundary temperatures on the combustion chamber surface in the steel piston start from 550°C [8].

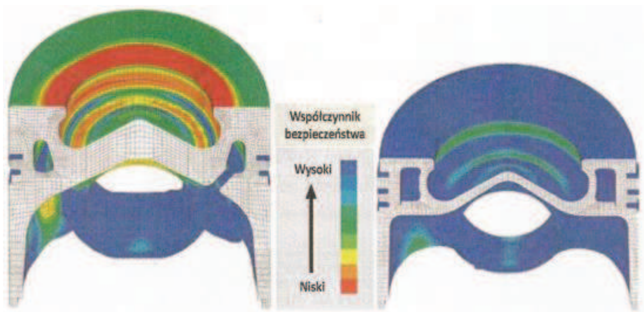


Fig. 5. Distributions of safety factor in aluminum and steel pistons [8]

The temperature of lubricating oil is not insignificant. If correctly regulated, it can reduce fuel consumption because the constant optimum temperature of the piston enables us to achieve such oil viscosity so that friction losses are reduced. Piston temperature can be indirectly controlled by changing oil temperature by regulating the oil flow. By controlling the oil flow, piston temperature can be modified within the range up to 50°C. The simulations by [6] to compare the capabilities of steel and aluminum pistons operating under the same conditions showed advantages and disadvantages of these solutions, see Table 1.

Table 1. Properties of steel pistons as in [6]

Advantages of steel pistons vs. aluminum ones	Disadvantages of steel pistons vs. aluminum ones
– higher temperature on the piston surface improves combustion, – reduced friction losses resulting from the smaller bearing piston surface and a lower thermal expansion, – better strength, – better strength to tribological wear, – the ability to reduce fuel consumption, – the ability to reduce toxic emissions, – the ability to increase the maximum cylinder pressure.	– lateral movements of the piston when the stroke begins and related piston strokes against the cylinder wall result in much wear of the piston skirt and a smooth section of the cylinder and increased noise, – high piston temperature can lead to carbonization of lubricating oil.

MAHLE's pistons are made of several different aluminum alloys. Pistons for CI engines are made of the eutectic alloy AlSi12Cu4Ni2Mg. The detailed composition and properties of this alloy have been provided in MAHLE's technical book [10, p. 67]. Aluminum-silicon pistons are usually cast but for special purposes forged as well. Forging changes the microstructure and properties of the element. Strength of pistons can be improved by the use of composite materials, namely aluminum alloys with a ceramic fiber, which can locally strengthen the most exposed sections, e.g. combustion chambers in the diesel engine. If aluminum pistons are not strong enough, iron-based materials can be used. This type of material can only locally reinforce the piston or iron or forged steel can be used for the entire piston. Pistons in heavy-duty diesel engines are chiefly made of cast iron. This material is used, for example, for monobloc pistons or composite piston skirts. Steel pistons can be made of two types of specially heat-treated steel: 42CrMo4 and 38MnVS6. This type of pistons are ideal for temperatures up to 450°C. When engines are tested, even higher temperatures of 500-550°C are possible, and then iron begins to peel as the result of its reaction with excess oxygen from an air-fuel mixture. If pistons operate at such temperatures, antioxidant coatings or other heat-resistant steels can be applied then. Generally, coatings prevent from a local melting of a material or its rubbing. In typical operating conditions, extra coatings are not necessary, but if there is extremal load – insufficient clearance due to the deformation of the cylinder, insufficient lubrication (at cold start, for elevated-temperature operation or used-oil operation), a new, not run-in engine, protective coatings prevent engine seizure. Samples of the coatings used by MAHLE are described in its technical book [10, pp. 79-81].

Cerit and Coban [3] examine the distribution of temperature and thermal loads acting on ceramic-coated aluminum pistons. The piston head was coated with magnesia stabilized zirconia powders. The temperature of the so coated piston is much higher than that of the non-coated one. The following figures show the test results.

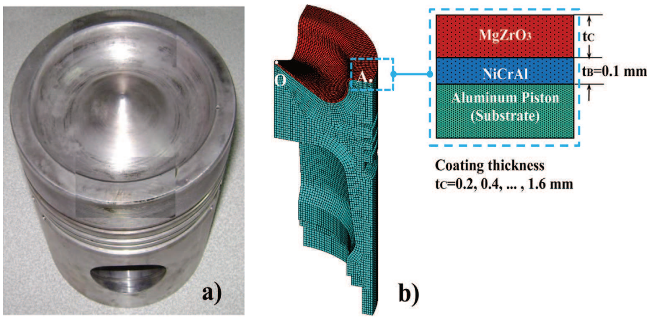


Fig. 6. Piston in the research: a) piston, b) coating mesh, coating composition and its parameters [3]

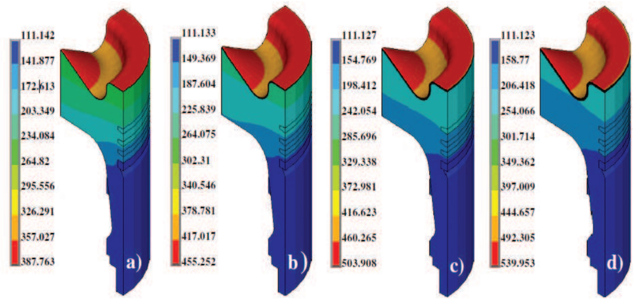


Fig. 7. Distribution of temperatures of the upper section of the coating for varied coating thickness: a) 0.4 mm, b) 0.8 mm, c) 1.2 mm, d) 1.6 mm [3]

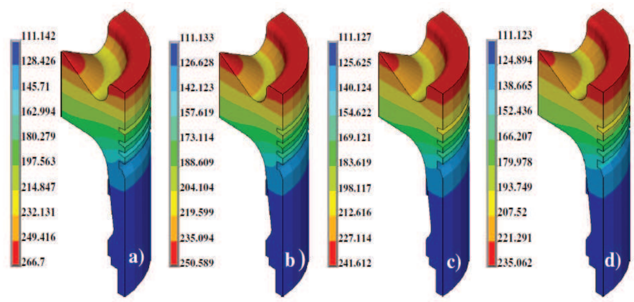


Fig. 8. Distribution of temperatures of the bottom section of the coating for varied coating thickness: a) 0.4 mm, b) 0.8 mm, c) 1.2 mm, d) 1.6 mm [3]

Higher temperatures in the combustion chamber are possible if coatings are applied to be a thermal barrier so engine's thermal efficiency increases. Decreasing piston temperatures under the coating improves engine performance. Clearly, the maximum thermal stress is a function of coating thickness. Maximum standard and tangential thermal stresses occur where the coating connects.

5. Cooling the piston

The piston is exposed to higher thermal loads because modern internal combustion engines are usually very loaded. Safe and reliable operation is possible if there is efficient cooling. A profile of CI engine piston temperature depends on the number and orientation of injection nozzles, injection pressure, injection timing and combustion chamber geometry. Importantly, the increase in temperature is accompanied by the even by 80% decrease in material fatigue strength, and iron-based materials are much less sensitive to temperatures of up to 400°C. Depending on the method of cooling, the difference can be even up to 50°C. The method of cooling depends on the amount of heat to be released [10].

Certain interesting research on cooling CI engine pistons was done in China in 2016 [23]. The paper discusses a new method of theoretical calculations to design pistons. A model of a piston for the 16V280 CI engine was investigated. The highest temperature was on the edge of the combustion chamber.

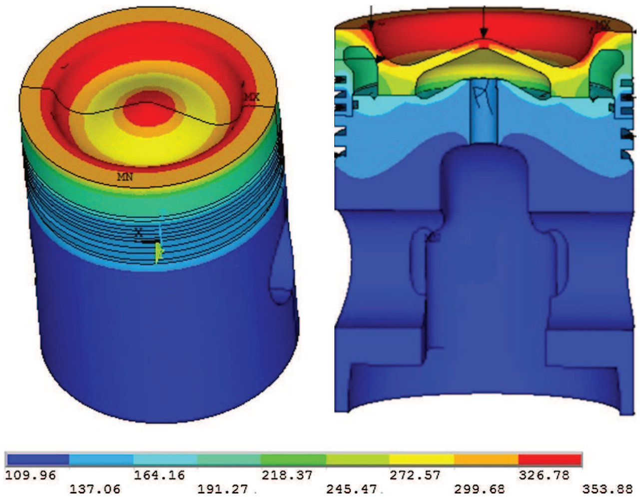


Fig. 9. Distribution of temperatures on the piston surface and inside the piston [23]

The distribution of piston head temperatures is very complex. The cooling method of cooling channels significantly impacts on cooling efficiency, and most of the heat from the piston is released to oil. The distribution of thermal stress in each measuring point is similar to that of mechanical stress so thermal stress cannot be ignored.

In the paper [5] investigated different piston configurations to find the most efficient cylinder air motion. Out of the examined shapes of the combustion chamber, the best one to achieve favorable conditions for combustion is a combustion chamber centrally mounted on the piston.

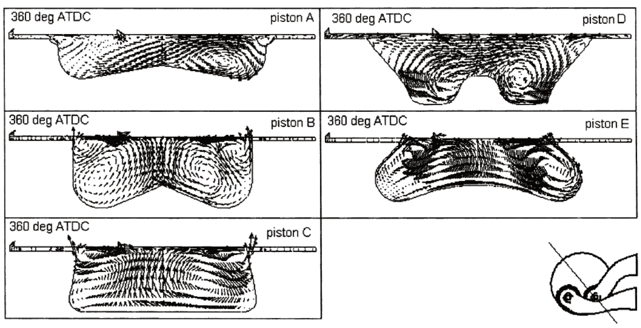


Fig. 10. Vectors of speed at TDC for 5 types of combustion chamber [9]

Payri et al. investigated in slightly more complex tests different configurations of the combustion chamber. Their research confirmed that piston geometry hardly impacts the in-cylinder flow during the intake stroke and the first part of the compression stroke unlike the shape of the combustion chamber which is important near TDC and in the early outlet stroke [9].

Another authors [11] discuss how combustion chamber turbulence and toxic emissions are impacted by shapes of the piston head and the injector nozzle. The figure below shows the combustion chamber geometry and the shape of the injectors to have been investigated.

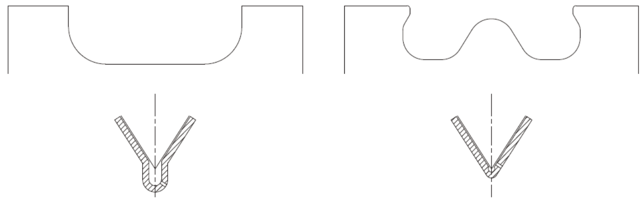


Fig. 11. Geometry of the combustion chamber and the nozzle endings; standard version – left, modified version – right [11]

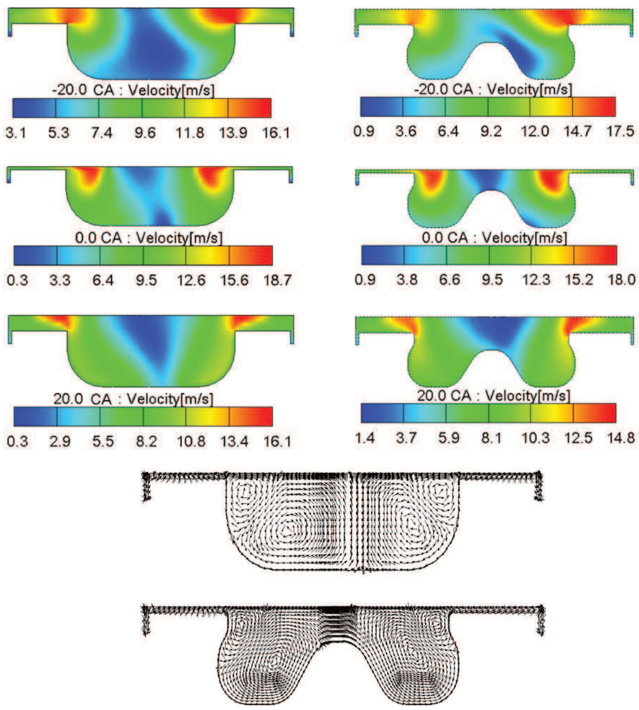


Fig. 12. Distribution of flow speed in the piston central section and vectors of speed in the piston central section at TDC [11]

The second configuration enabled lower toxic emissions. The CFD simulations showed that the shape of the combustion chamber was not so important as the changed shape of the injector. The author concludes that a negligible impact of the changed shape of the combustion chamber results from, e.g. a larger surface area and a large central projection inside the combustion chamber.

CFD tools have been used to develop further the shape of the combustion chamber, the geometry of the piston and fuel injection parameters in a new 2-liter ECOBlue CI engine mounted in the Ford Transit. It was the first time when the Ford had a mirror layout of intake channels so air could reach the first two cylinders by clockwise swirling and the latter two by counterclockwise swirling. This method enabled better in-between cylinder air distribution, which significantly helped reduce emissions and fuel consumption (by 13% relative to the previous version) [7].

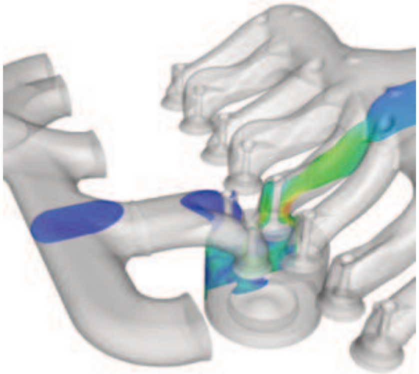


Fig. 13. CFD simulation in the ECOBlue [7]

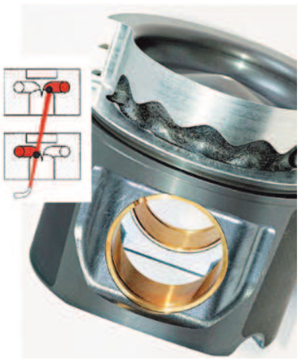


Fig. 14. Oil flow in the dual piston gallery [20]

Federal-Mogul Corporation has created a new piston design with a dual coolant loop gallery. The heat from the piston head is released more efficiently and operating temperature of the piston is lower. The following figure shows the oil flow. The figure depicts the upper and lower piston position when the coolant fills alternately the right and left piston gallery section. This type of solution has been applied in the Mercedes-Benz OM 500 [7].

6. Summary

The investigation on the construction of pistons dedicated to the compression-ignition engine focused on the development trends, especially in material applications and cooling improvement. The paper overviewed the history of aircraft compression-ignition engines and the factors behind the revived interest to improve this type of engines, and particularly piston-opposed engines. The higher permissible engine load has led to the solution of steel as alternative material. Steel pistons enable, among others, better combustion as higher temperatures on the piston surface and higher maximum cylinder pressure could be achieved. Such changes also require us to improve piston cooling. This paper discusses the solutions followed by certain automotive companies.

Acknowledgement

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Nomenclature

CFD computational fluid dynamics
CI compression ignition
R&D research&development
TDC top dead centre

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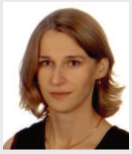

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