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DESIGN OF AN INNOVATIVE NATURAL GAS TWO-STROKE ENGINE

P. Diwisch, C. Dinkel, F. Rieg and B. Alber-Laukant

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1. Introduction

High-speed two-stroke engines in the field of small hand-operated devices, Jet Skis, snowmobiles, motorboats and ultralight aircrafts have a large market share. In Asia, two-stroke engines are predominantly applied in motorcycles [Meinig 2001]. Due to rising demand on exhaust emissions, two-stroke engines are less and less employed despite considerable advantages. In contrast to four-stroke engines, two-stroke engines fire at each crankshaft revolution. Thus, besides a more even progression of torque a bisection of the mean effective pressure is achieved. As a result, higher power density as well as minor construction volume can be obtained. Concerning the prospective usage of two-stroke engines the progress in adherence to emission standards will be decisive. This would also enable the development of further areas of application. Hence, possible applications of two-stroke engines include the usage as a range extender in electric vehicles to increase their range and customer acceptance as well as the usage in combined heat and power stations (CHP). Therefore, the Chair for Engineering Design and CAD, under the direction of Prof. Dr.-Ing. Rieg at the University of Bayreuth, focuses on the constructive improvement of scavenging caused fuel consumption and thus hydrocarbon exhaust emissions concerning two-stroke engines. The realization consists of two phases. During the first stage the selection of a suitable concept for a two-stroke engine takes place. Within the second phase several existing computer-aided technologies are combined through "intelligent cross-linked simulation" (ICROS). Since the development of a two-stroke engine includes elaborate simulations of both thermofluid dynamics and combustion, ICROS has to be combined with a validation method. The response and integration of information, gained by the validation method, into the iterative process leads to an extended ICROS method which will be introduced in the following chapters on the basis of the cylinder head of a two-stroke engine. This leads to a faster and more economical product development process of essential parts for an innovative two-stroke engine with substantially high efficiency and reduced exhaust emissions of hydrocarbon.

2. Theoretical foundations

The required scavenging generally determines the characteristics of the two-stroke engine, possible scavenging losses, fuel consumption and the exhaust emissions of hydrocarbon. Consequently, the aim is to achieve the most ideal charge cycle, which is characterized by no intermingling of fresh and exhaust gas and even short circuits. The chosen method usually influences installation space, weight, pollutant emissions as well as the demand for further components. The different scavengings can be quantified by the three parameters charging efficiency, volumetric efficiency and trapping efficiency. In chapters 2.2 and 2.3 established scavengings will be represented.

2.1 Charging efficiency, volumetric efficiency and trapping efficiency

In order to evaluate the charge exchange, the knowledge of the amount of gas that remains in the cylinder is essential. This also applies to the proportion of unburned hydrocarbons that enters the exhaust system during the scavenging process. These two quantities are determined by charging efficiency, volumetric efficiency and in the case of two-stroke engines particularly by trapping efficiency. Charging efficiency λ_L is defined as the quotient of the air-fuel mixture in the cylinder m_z before ignition and the theoretically maximum charge of fresh gas m_{th}. Thus, Equation (1) describes the residual-gas share of the cylinder charge.

$$\lambda_L = \frac{m_Z}{m_{th}} \tag{1}$$

Since flow losses occur, the charging efficiency of naturally aspirated engines is <1. Charged engines reach values of >1 [van Basshuysen and Schäfer 2015].

If a long valve overlap occurs, which means that inlet and outlet are opened simultaneously, short-circuit currents can emerge. During this process a mixture of fresh gas and fuel get out of the cylinder into the exhaust system and caused emissions of unburend hydrocarbons. Hence, it is not available for the combustion anymore. Therefore, the mass of the overall supplied air-fuel mixture m_G differs from the mass in the cylinder before the ignition occurs. Concerning the largest possible mass of fresh charge in the cylinder m_{th}, volumetric efficiency λ_{La} can be calculated according to Equation (2).

$$\lambda_{La} = \frac{m_G}{m_{th}} \tag{2}$$

The characteristic variable for the fresh gas remaining in the cylinder is expressed by the trapping efficiency λ_F. It is the ratio of charging efficiency λ_L to volumetric efficiency λ_{La}.

$$\lambda_F = \frac{\lambda_L}{\lambda_{La}} \tag{3}$$

2.2 Functional principle of a loop scavenging two-stroke engine

Nowadays, loop scavenging is the most common type of gas exchange in the sector of high-speed two-stroke engines. Simplified, the engine consists of the parts piston, connecting rod, crankshaft and cylinder, in which inlet and outlet ports are opposed. In order to complete one power cycle per crankshaft revolution, a gas exchange has to take place in the bottom dead center. The piston controls the scavenging by opening and closing the ports. For this purpose, pressurized air is essential. In most designs this is achieved by an interaction of crankcase and oscillating piston, called crankcase scavenging. As a result, a separation of the air-fuel mixture and the lubricating oil supply is impossible. The same applies to the use of a piston crown cooling for reducing the asymmetrical thermal load of the piston. If both ports are opened the gas exchange can proceed. According to Figure 1 fresh gas rises on the opposite wall of the inlet ports towards the cylinder head, changes its direction and flows into the exhaust system.

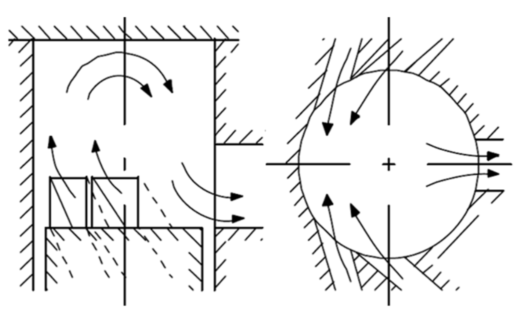

Figure 1. Loop scavenging according to [van Basshuysen and Schäfer 2015]

During this process short-circuit currents between inlet and outlet ports occur, which lead to both an increase in hydrocarbon emissions and a reduction in the trapping efficiency λ_F. These flows are encouraged by closing the exhaust systems after the scavenged ports. Only now the compression procedure can begin. To decrease the hydrocarbon emissions by generating an asymmetrical engine timing, additional parts such as rollers or slides are required. Moreover, it is often tried to achieve the exhaust emission standard by using direct injection systems. Here, scavenging with fresh air is supposed to reduce hydrocarbon emissions. After closing the outlet port the fuel is injected in the cylinder. However, the direct injection system increases the complexity of the two-stroke engine and thus is inconsistent with the initially economical, compact and simple design. Further possibilities to minimize hydrocarbon emissions are alternative scavenging processes as well as suitable engine designs [van Basshuysen and Schäfer 2015].

2.3 Functional principle of a uniflow two-stroke engine using outlet valves

Low-speed two-stroke diesel engines achieve the highest degree of efficiency among internal-combustion engines [Urlaub 1995]. A widespread gas exchange concept among low-speed engines is the uniflow scavenging with outlet valves depicted in Figure 2. This design does not only contain components such as pistons, connecting rods, a crankshaft and cylinders with inlet ports but also a valve train and poppet valves. Since a gas exchange has to take place in the bottom dead center, a self priming is not possible. Instead a pressure gradient is required. Usually, exhaust gas turbochargers are used to generate pressurized air.

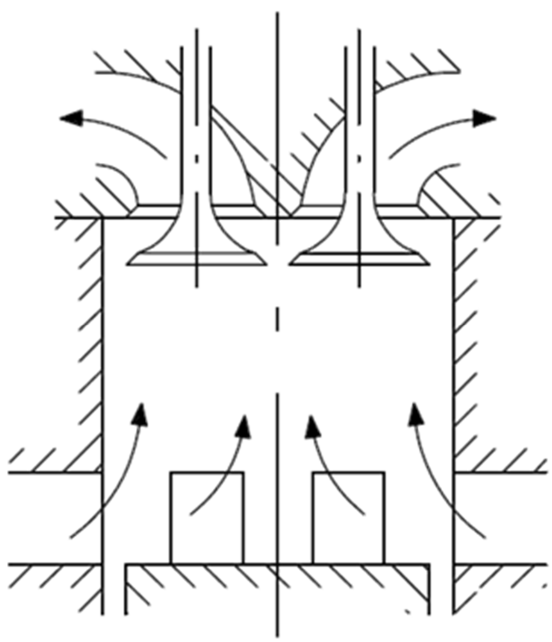

Figure 2. Uniflow scavenging [van Basshuysen and Schäfer 2015]

However, this approach demands further technical measures to produce pressurized air during the starting process. In contrast to the crankcase scavenging, the crankcase is not used to generate pressure anymore. Therefore, a separation of the fuel-air mixture and the lubrication oil supply takes place. The minimization of lubrication oil in the exhaust gas is a positive consequence of this construction. The scavenging starts by opening the exhaust valves. Asymmetrical engine timing can be achieved by adjusting the valve train. This enables opening the outlet valves before the inlet ports. Once the exhaust gas escapes through the outlet valves due to small combustion pressure, the inlet ports will be opened by a downward movement of the piston. Fresh gas enters the combustion chamber and drives out the remaining exhaust gas. This kind of gas exchange is called uniflow scavenging. It can be characterized by a small mixture of fresh and exhaust gas and hence a high charging efficiency λ_L. After closing the outlet valves the inlet ports are still opened for supercharging. The inlet ports will be closed by an upward movement of the piston, which leads to a compression of the fuel-air mixture until ignition takes place. However, the advantages of these kind of uniflow two-stroke engine oppose a larger design as well as additionally required components including a valve train and an exhaust valve.

3. Scavenging process and fuel influence

To reduce emissions of hydrocarbon in modern two-stroke engines it is important to avoid scavenging losses. Hence, both better emissions and less fuel consumption are possible. The implementation of a new EU law that regulates the emissions of hand-operated devices predominantly forced the development of the scavenging in two-stroke engines. To follow the law a carburettor and two parted inlet ports are applied. During the downwards movement of the piston the first inlet port filled with fresh air is opened. After the scavenging process with the pure air has taken place, the second inlet port is opened. Now, the scavenging with a air-fuel mixture is performed. By applying this process to hand-operated two-stroke devices, emissons close to those of four stroke engines can be achieved [Weber 2015].

Larger loop scavenging two-stroke engines are equipped with a gasoline direct injection system. Thus, the scavenging fresh-gas consists of air only. After closing the inlet and outlet ports by the upwards movement of the piston, the fuel is injected into the cylinder. This leads to less hydrocarbon emissions and a decrease of fuel consumption by 35 % compared to carburettor systems [Bartsch and Henrichs 2014].

By using an alternative fuel like natural gas, emissions can be reduced significantly. Besides reduced emissions, natural gas can be generated out of renewables. Therefore, Biogas is treated to meet the quality of natural gas. A study that exmines the potential of LPG and CNG as energy sources to reach a sustainable energy supply of the road traffic [Heidt et al. 2013] shows that the emissions of natural gas driven four-stroke engines compared to gasoline ones can help to decrease the emissions of CO_2 by 25 %, NO_x by 10 %, fine particles by 10 % and carbon hydrogen by 82 %. These engines are operated by the principle of injecting natural gas in the intake duct. The concept of a natural gas direct injection system is currently not available. Accountable for this are less lubrication and cooling effects of natural gas, stringent requirements on leakage because of a low gas density and hence greater costs [Westerhof 2016].

The combination of the advantages of a natural gas operated engine with a two-stroke engine affords another way of reducing the scavenging losses instead of using direct injection. The state of the art at four stroke engines is to inject natural gas in the intake duct. The simple transfer of this kind of fuel injection system to loop scavenging two-stroke engines is not possible. Short-circuit currents would cause unburned methan in the exhaust system which would lead to a high fuel consumption. Nevertheless, the future-oriented advantages of natural gas driven engines require the implementation in two-stroke engines to achieve a competitive engine. Therefore, it is necessary to find a solution to avoid short-circuits in combination with an intake-manifold fuel injection during the scavenging process.

4. Definition of aim and method for realization

The Chair for Engineering Design and CAD focuses on the development and implementation of a solution concept concerning the reduction of scavenging caused fuel consumption and hydrocarbon exhaust emissions of two-stroke engines. The aim is to obtain a concept that combines the advantages of a compact and economical design as well as the high power density of the high-speed two-stroke engine with the advantages of the low-speed two-stroke engine. These comprise low volumetric efficiency λ_{La} and decreased short-circuit currents. In order to encompass a wide range of applications in the future, a bivalent operation with bioethanol and especially natural gas generated out of biogas has to be introduced.

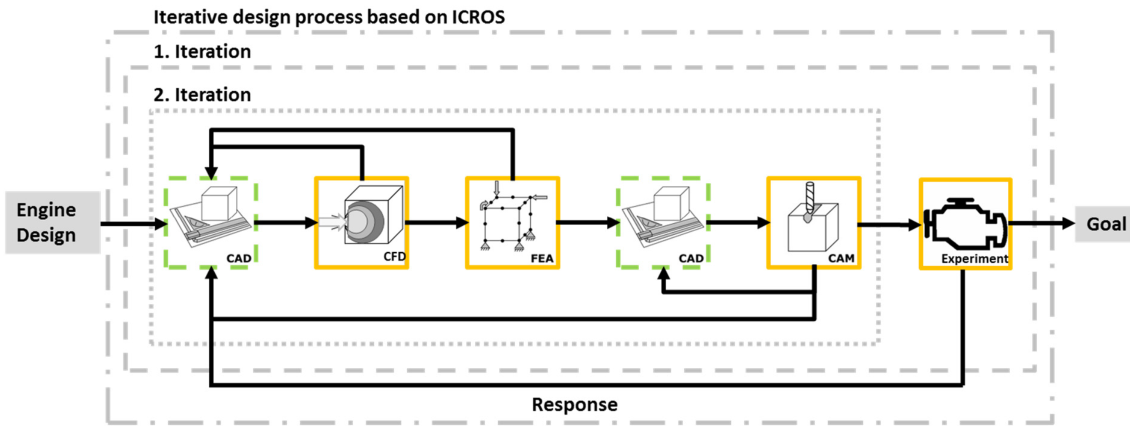

Figure 3. CAx chain according to [Zapf et al. 2010]

According to Figure 3 the realization consists of two stages. The first phase comprised the selection and adjustment of a suitable engine concept by sighting various different concepts considering the objective. The following phase proceeds with the drafting and production. To accelerate the developing process, a variety of prototypes were dropped and replaced often by several CAx systems [Dolsak et al. 2004]. The selection and combination of suitable, already existing and cheap programs, their range of functions and the chronological order within the developing process describe a great challenge. An appropriate method for selecting and linking various CAx systems is offered by ICROS (intelligent cross-linked simulation) [Alber et al. 2006], that was developed by the Chair for Engineering Design and CAD at the University of Bayreuth. ICROS has already been successfully applied to develop polymeric components and in the context of a dissertation named "Struktur- und Prozesssimulation zur Bauteildimensionierung mit thermoplastischen Kunststoffen: Validierung von Werkstoffbeschreibungen für den technischen Einsatz" (English meaning: structural and process simulations for component designs with thermoplastic polymers: validation of material descriptions for technical use) [Alber 2008]. It includes references to CAx systems such as CAD, Mould Modelling, FEA and CAM. Similar to the development of polymer components, CAD models of single parts are created when generating a two-stroke engine. Moreover, the components' solidity and producibility are examined and if applicable optimized. Instead of applying the flow simulation for finding an appropriate moulding connection, it is used to examine those parts that are essential for the exchange process and the cooling. As it concerns elaborate thermal flow simulation and the simulation of combustion, a validation of the results is inevitable for a successful implementation. Owing to a remarkable resemblance and simple transmission, ICROS is utilized to accomplish the realization of single parts of the two-stroke engine. For this purpose an extension of the iterative decision-making process of ICROS has to take place. This enlargement contains the coupling as well as the integration of an appropriate validation method. In the present case of application the experiment was chosen due to gain as realistic results as possible. Since an already developed and produced prototype is needed for this, its incorporation takes place at the end of the CAx processes selected by ICROS. However, the validation of results at the end of the product development process proved very risky. When applying this approach, modelling errors would only be detected after the production of the elaborate components. Therefore, this would negatively affect the costs and development time and thus contradicts the demand to reduce expenses and the complexity of the product development process [Stöber et al. 2009]. In order to solve this problem, the iterative design process has to be passed twice. During the first iteration, an expedited run takes place. It involves the development of a prototype characterized by a simplified geometry and a less extensive requirements specification. This enables not only an economical production but also a validation of the results. If the simulation results coincide, a detailed and appropriate elaboration through those CAx systems selected by ICROS can take place. If the results differ, however, an examination of both the experiment and the simulation has to ensue.

5. Design of an innovative split-single two-stroke engine

5.1 Design of the engine

The comparison of several engine designs shows that the objectives mentioned can be achieved by a split-single two-stroke engine [Laimböck 1985] using a uniflow scavenging. In contrast to the functional principle of a uniflow two-stroke engine described in 2.3, this design does not need any outlet valves. Instead of them, exhaust ports steered by an piston are applicated. In contrast to an opposed-piston engine, this concept ensures a compact design and does not require a second crankshaft or push rods. Figure 4 illustrates sectional views of the redesigned split-single engine at a crank angle of 120°, 240° and 360°.

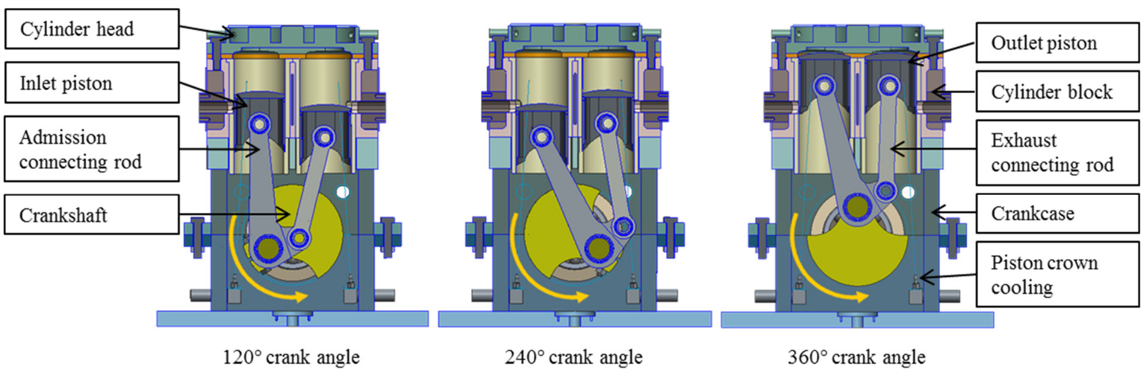

Figure 4. Split-Single Two-Stroke Engine by Prof. Dr.-Ing. Rieg based on a racing design of DKW developed in the 1930s

According to this design, two pistons share one combustion chamber. While one of those pistons controls the inlet ports the other operates the exhaust port. Both pistons are linked by a Zoller connecting rod, which consists of an exhaust connecting rod and an admission connecting rod. Figure 4 on the left shows the position of the pistons at a crank angle of 120°. The exhaust port opens due to the downward movement of the outlet piston, while the inlet is still closed. Hence, the exhaust gas can get to the exhaust pipe. At a crank angle of 135° to 225° the inlet and outlet ports are open simultaneously and the uniflow scavenging takes place. Since the outlet port with the higher thermal load closes before the intake at a crank angle 225°, the hydrocarbon in the exhaust gas decreases while the supercharger effect is maximized between a crank angle of 225° and 260°. Moreover, a decrease in short-circuit losses can be achieved by a greater distance between inlet and exhaust ports. The volumetric efficiency λ_{La} also reduces through the above mentioned features.

In the 1960s this engine design has already been used to produce motorcycles. Today the concept served as a basis for the split-single engine developed by Prof. Dr.-Ing. Rieg based on a racing design of DKW developed in the 1930s. In order to reduce the unburned hydrocarbon even further, the redesigned construction does not apply total-loss lubrication, which means that there is no mixture of oil lubrication and gasoline. Concerning fuel flexibility, this is also essential, as the mixture of ethanol and lubrication oil proved inappropriate [Ferrari et al. 2012]. Therefore, a separation of lubrication oil and gasoline is inevitable. A lubrication of the components is achieved by oil feeder holes located in the crankcase. Due to an additional piston crown cooling, the temperature of the outlet piston with the higher thermal load can be reduced. Depending on the mode of operation, plain bearings can be used to increase both the lifetime and the maintenance interval because of a wet sump lubrication. Considering that the application of plain bearings causes higher friction losses, rolling bearings are used to reduce the consumption of gasoline [Tiemann et al. 2007].

Owing to the essential separation of the lubrication and gasoline system as well as a low precompression ratio, the crankcase scavenging is not used anymore [Laimböck 1985]. This enables the development of a bivalent fuel-driven engine. The precompression of the fuel-air mixture is realized by a exhaust gas turbocharger. Advantageous is the additional transformation of the exhaust energy which would remain idle otherwise.

A precise adjustment of the turbocharger to the specific operation point can take place by means of variable turbine geometry (VTG). This adjustment is particularly important in the partial load operation to avoid emitted hydrocarbon caused by a low charging efficiency λ_L through misfiring. In order to ensure adequate scavenging during the starting process, the electric motor has to be linked with the exhaust gas turbocharger.

A map-controlled ignition and injection is used for the fuel supply and the ignition. The adjustment of the injected fuel quantity and the correct firing point, to avoid misfiring, is regulated by the input variables rotational speed, throttle position, intake pressure, coolant temperature as well as lambda value. At a crank angle of 135° to 225° both kinds of ports are opened. The choice of a suitable injection valve that fits to the ports overlap-time allows the application of a two-part scavenging process to further reduce the hydrocarbon emissions. In the first part of the scavenging fresh air suppresses the exhaust gas out of the cylinder. In the second part the required amount of fuel is injected in the intake duct and is mixed with fresh air. Before closing the outlet ports the ignitable mixture gets into the cylinder. Furthermore, an activation of multiple spark plugs and ignition processes counteracts an adverse combustion chamber geometry by inflaming the fuel-air mixture.

The sufficient heat dissipation at the cylinder head, the cylinder block and at the thermally stressed area between the two pistons is ensured by a forced circulation cooling. The cooling system can also be linked through suitable interfaces with heat consumers. The application of the engine as a combined heat and power station or as a range extender in a compact car requires a performance of 15 kW to 50 kW [Merker and Teichmann 2014]. Therefore, the performance of the redesigned engine has to meet these conditions. The maximal power of 37 kW should be reached at a nominal speed of 3000 rpm and a cylinder volume of 500 cm³.

5.2 Application of ICROS in the design process of the cylinder head

A prototype of the split-single engine has already been produced by the Chair for Engineering Design and CAD and has been tested on the engine test stand. Test beds are used to examine mechanical components, to validate numerical simulation and to measure realistic boundary conditions. Both previous tests performed on the test bed and run simulations of the prototype engine confirm the concept of the split-single engine. Optimizing the different components constitutes the next step that will follow. To achieve the performance of 37 kW a modification of the cooling system and a piston crown cooling in the area of the outlet piston with the highest thermal load are necessary. The improvement of the cylinder head was realized at first due to reasons of production. To accelerate the production of a suitable cylinder head the development process was carried out with the help of a extended version of ICROS. This includes the computer programs PTC Creo, Ansys CFD, Z88Aurora and Vericut. These programs are available at the Chair for Engineering Design and CAD. The construction and manufacture process was realized by using PTC Creo. The existing interface with the CNC fabrication machines allows a simplified production. To avoid mistakes, the fabrication milling processes were controlled by using Verticut. The thermal simulation as well as the simulation of the combustion was realized by Ansys CFD. Finally, Z88Aurora was used to examine the displacements and to proof the strength of the parts. Figure 5 illustrates this schematic sequence of the development process on the basis of the cylinder head. Since the development of a cylinder head involves static, thermal and transient flow simulations as well as simulations of combustion with moving components, a validation of these complex linked simulations is inevitable. In order to receive the fastest feedback possible concerning the validity of the chosen simulation model, the application of the first iteration cycle is essential. Owing to the swift production of the component, its requirements have to be decreased. Accordingly, the intended engine performance is 22 kW. Since the first draft of the cylinder head displayed insufficient heat removal during the thermal flow simulation, a further flow simulation was performed to detect dead-water areas. In order to reduce these areas the steel geometry was revised. Accordingly, a subsequent simulation showed an adequate heat removal. Moreover, the strength verification was reviewed by a finite element analysis, while the producibility was confirmed by using the CAM software. Assembled in the engine test stand, the power measurement took place. As the values of simulations and the measurement matched, the actual product development process including all required boundary conditions could begin. Due to the results gained by the first iteration and transferred to the second one, an appropriate geometry was designed that meets the requirements. This tripartite cylinder head made of aluminium alloy has already shown great potential during thermal and static flow simulations, which was confirmed by the engine test stand. Thus, only the improvement of the cylinder head through ICROS led to a performance of 33 kW, which corresponds to a increase of 50 %. Now, the next objectives are to upgrade the cylinder block cooling and to apply the piston crown cooling. These means are aimed at achieving the intended performance.

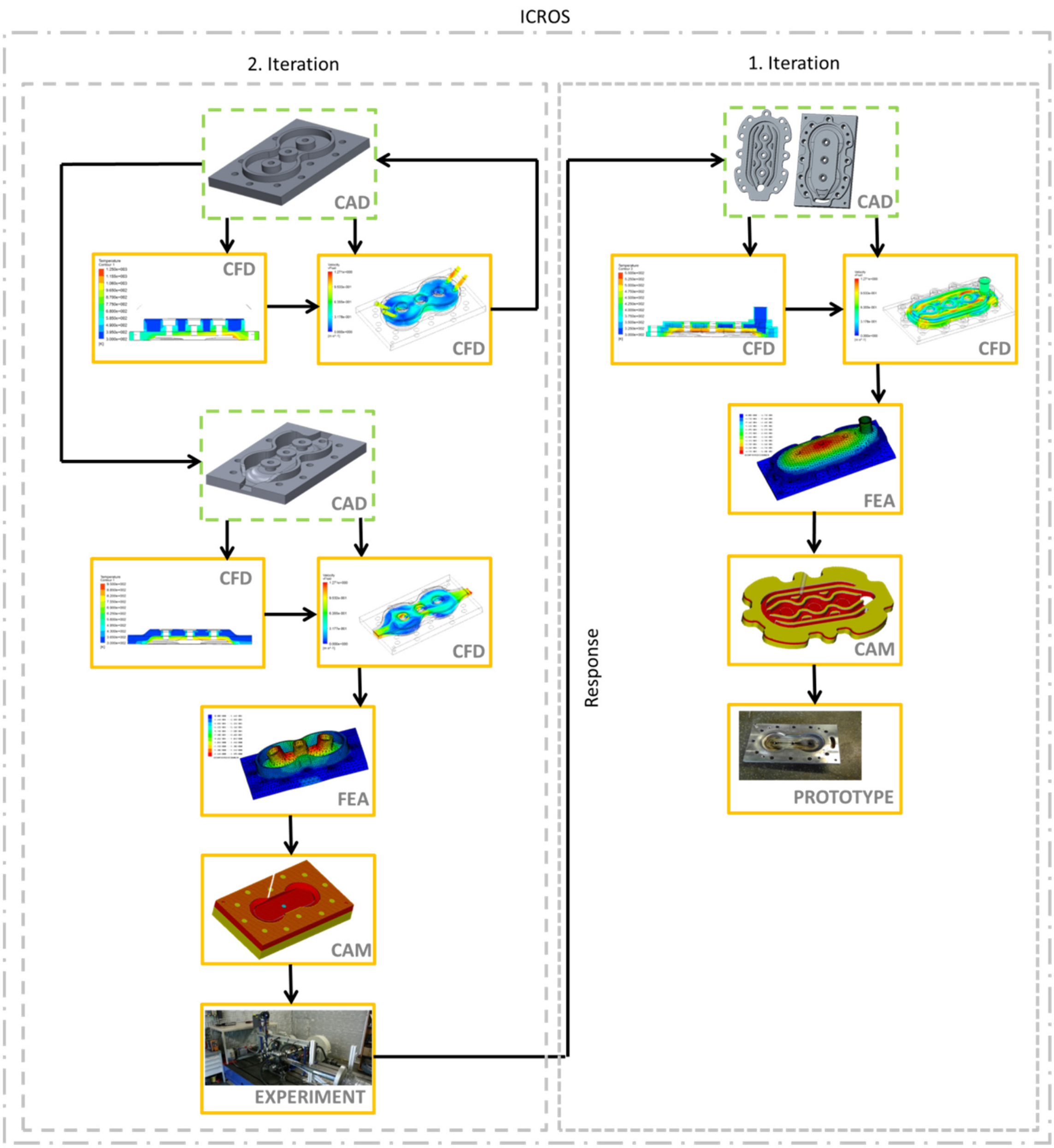

Figure 5. Extended ICROS applied to the cylinder head

6. Conclusion

Due to their compact design, a high power density and a more even torque curve, two-stroke engines are most suitable for both the application as range extenders in electric cars and combined heat and power stations. However, a high fuel consumption and hence increased hydrocarbon emissions caused by short-circuit currents and misfiring in the partial load operation are responsible for a decrease in demand of two-stroke engines. To counteract these development, direct fuel injection systems are introduced in two-stroke engines. The advantages of using natural gas instead of gasoline are significant since it causes less exhaust emissions and can be obtained out of renewables. Therefore, it is essential to apply natural gas to two-stroke engines. Since direct injection systems for natural gas are currently not available because of less lubrication and cooling effects it is necessary to find another way to reduce short-circuit currents. Therefore, the Chair for Engineering Design and CAD is concentrating on the development of a two-stroke engine that prevents short-circuit currents through a specific flow design called uniflow scavenging. Sighting former engine designs led to the promising concept of a split-single two-stroke engine.

To prohibit misfiring in the partial load operation a map-controlled ignition and injection coupled with an exhaust gas turbocharger is applied. The substitution of a wet sump lubrication for total-loss lubrication further facilitates a bivalent fuel-driven engine. For the realization of essential parts of the split-single two-stroke engine the ICROS-method is used, which is extended by a validation method. This new expanded version of ICROS consists of two iteration cycles. Its practicality was demonstrated by means of the development process of the cylinder head.

The next targets will be the development of a combustion chamber as well as a cylinder block cooling using the improve ICROS. Finally, the suitability of the revised prototype will be proved of its possibility to reduce short-circuit currents and hence to decrease the fuel consumption and the emissions of hydrocarbon.

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Pascal Diwisch, M.Sc.
University of Bayreuth, Chair of Engineering Design and CAD
Universitaetsstrasse, 30, 95447 Bayreuth, Germany
Email: pascal.diwisch@uni-bayreuth.de