

Future Engine Technology in Hand-Held Power Tools

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ABSTRACT

Today mankind is using highly sophisticated tools which contribute to maintain the standard of living. Nevertheless, these tools have to be further improved in the near future in order to protect health and environment as well as to ensure prosperity. Two-stroke engines equipped with a carburettor are the most used propulsion technology in hand-held power tools like chain saws and grass trimmers. The shortage of fossil resources and the necessary reduction of carbon dioxide emissions ask for improved engine efficiency. Concurrently, customers demand for an easy usage with high performance at all operating conditions, e.g. varying ambient temperature and pressure and different fuels. Moreover, world-wide emission limits will be even stricter in future.

The improvement of the emission level, fuel consumption and customer benefits, while keeping the present advantages of two-stroke engines, like high specific power and simplicity, are the goals of this research work. This paper describes the experimental results of several low-cost electrical mixture formation systems (low pressure direct injection, semi-direct injection and external mixture formation) in combination with a two-stroke engine. 3D-CFD simulations have supported the experimental investigations in order to gain insight into the complex interactions. Based on simulation and experimental results, the fundamentals of the different mixture formation processes are discussed. The results indicate potential for reducing emissions and fuel consumption while gaining additional benefits for the customer. With these improvements the two-stroke engine technology will likely be still the most used engine technology in hand-held power tools in the future although competitors like four-stroke and electrical engines show great technical advances in this small engine technology segment.

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INTRODUCTION

Mankind is using tools from time immemorial in order to facilitate daily life. Hence, hand-held power tools like motor-saws, powered with an internal combustion engine, were developed in the nineteen-twenties for cutting trees. The development of light weight and universally applicable one-man motor-saws in the nineteen-fifties initialized the economic upswing of hand-held power tools. A best seller was for instance the Stihl Contra, which came on the market in 1959. This trend started the development of numerous hand-held power tools for other applications like grass trimmers, brush cutters, clearing saws, blowers and cut-off saws. High specific power, simplicity, low weight, low costs and a compact design are characteristics of these two-stroke engine powered applications. The use of piston-control or reed valves, a carburettor for mixture formation, oil-in-

gasoline lubrication and loop scavenging is well established. Inherent disadvantages are high fuel consumption, high engine-out emissions and changing operational behaviour during varying ambient conditions. Nevertheless, significant improvements regarding emission behaviour have been achieved during the last years because of stratified scavenging or exhaust gas-aftertreatment systems. The present emission level of 50 g/kWh for NO_x+HC (Nitrogen Oxide and Hydro Carbon) for engines up to 50 cm³ is fulfilled by these sophisticated two-stroke engines.

Novel mixture preparation and scavenging technologies provide high development potential for the future to reduce fuel consumption and to optimize exhaust gas emissions. At the same time the product has to be further improved in order to gain additional customer benefits, like ease of use and easy starting without cost increase in this price-sensitive market.



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The use of four-stroke and electrical engines are possible approaches for the future but these technologies have disadvantages regarding high specific power, simplicity and costs. On the contrary, these are the main strengths of two-stroke engines. If emissions, fuel consumption and customer benefits are improved, two-stroke engines will be a suitable solution for years to come.

Realizing these improvements, while keeping the present advantages of two-stroke engines, is the aim of this research work. The engine-out emission reduction competes with exhaust gas aftertreatment, which, with regard to temperature management and safety aspects, poses several challenges. Therefore, the main approach is to replace the carburettor by modern injection systems controlled by a hand-held capable ECU (Electronic Control Unit) in order to reduce the engine-out emissions and to improve customer relevant topics. This publication covers the experimental results of several low-cost electrical mixture formation systems (low pressure direct injection, semi-direct injection and crank case injection) in combination with a 47 cm³ two-stroke engine. 3D-CFD (Computational Fluid Dynamics) simulations have supported the experimental investigations in order to gain insight into the complex interactions. The requirements on engines used in hand-held power tools are analysed and serve as evaluation basis. The results of the prototypes are compared to a 47 cm³ series production two-stroke engine with stratified scavenging described in the literature as airhead [1]. Based on the simulation and experimental results, the fundamentals of the different mixture formation processes are shown below. In addition to that, pros and cons of the different prototypes regarding their engine control behaviour like idle speed control, start, engine speed limiting and transient behaviour are evaluated and assessed for the application in a hand-held power tool.

REQUIREMENTS ON HAND-HELD POWER TOOLS

A combustion engine used for the propulsion of a hand-held power tool has to fulfil various opposed requirements shown in Figure 1. The engine has to be simple, while a reliable operation under varying ambient condition has to be ensured. The demand for robust and simple technology with high power density leads to air-cooled single cylinder engines with engine speeds up to 14.000 rpm. Thus small displacements with ergonomic weight and packaging advantages are realizable. Most of the present applications have displacements between 20 and 80 cm³ with a specific power from 30 to 60 kW/l. Additionally, strict requirements regarding noise and vibrations are presupposed for health and safety which are likewise challenging.



Figure 1. Requirements on hand-held power tools

Also maximum surface temperatures and exhaust gas temperatures at prescribed distances are limited by legislature. Besides, emission legislation has to be fulfilled which is primarily not customer relevant. USA and EU have introduced strict emission limits, which other countries will use as a role model. A further reduction of emission limits is probable. The present emission test procedure is a steady state two-mode test cycle. The first operating point is at maximum power (100 % load) and produces 85 % of the overall weighted emissions of the engine. The second point is at idle operation and affects the residual 15 %. Future emission limits and their period of validity are still in discussion. Limited emissions by EPA [2] (Environmental Protection Agency) are HC+NO_x and CO emissions (Figure 2). Additionally, NO_x emissions are limited to 10 g/kWh in the EU. Furthermore, the manufacturer has to guarantee the limits in compliance with the emission legislation for the classified product life cycle (EPA regulation: 50, 125 or 300 h).

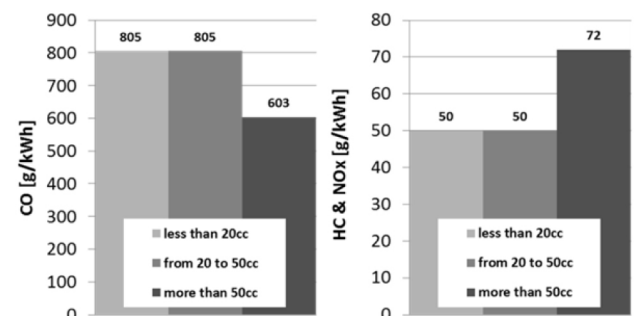


Figure 2. EPA Emission limits for different displacement categories

PRESENT TECHNOLOGY - REFERENCE ENGINE

A 47 cm³ series production two-stroke engine with stratified scavenging and a single-flow carburettor has been used as starting point for the investigations and as reference for the comparison of the results. This concept achieves significant low HC emissions for a two-stroke engine. [Figure 3](#) shows a section through the cylinder of the reference engine, and in [Table 1](#) the engine data is summarized.

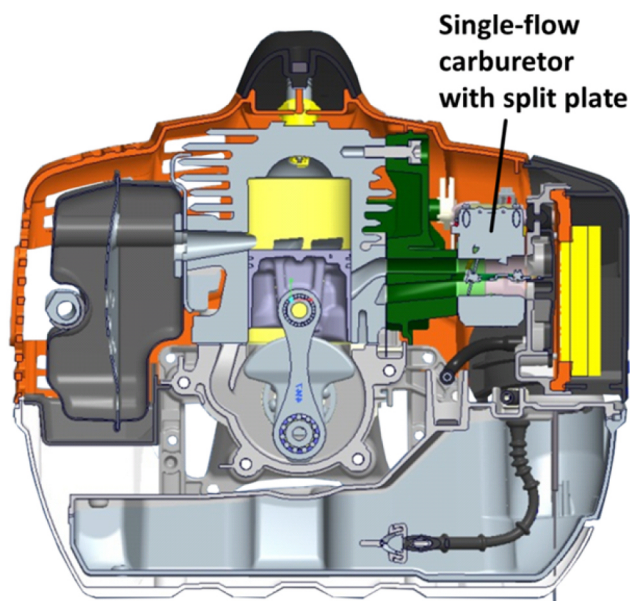


Figure 3. Reference engine - stratified scavenging with carburettor

The stratified scavenging principle was already mentioned in 1922 [3] and many papers and patents have been published since on the topic [1].

Table 1. Data of reference engine

Cylinder:	1-cylinder / air-cooled
Displacement:	47 cm ³
Compression ratio:	9.61
Specific power:	46 kW/l
Principle:	Loop scavenged / stratified scavenging
Ports:	Four scavenging ports / one exhaust port
Mixture formation:	Carburetor
Ignition system:	Magneto system
Max. engine speed:	12.000 rpm
Lubrication:	Oil-in-gasoline / 1:50
Exhaust aftertreatment:	Without

The reference engine uses crankcase compression and has a conventional air and fuel supply into the crankcase via a carburettor. The port configuration of the reference engine is

shown in [Figure 3](#) and [Figure 4](#). A single-flow carburettor with split-plate is used to separate the fuel supply from pure-air intake ([Figure 3](#)). An auxiliary inlet port connects the lower area of the parted carburettor (contains pure-air) via a recess in the piston to the scavenging ports close to their entry point to the cylinder. During the induction stroke the recess in the piston opens and pure air streams towards the crankcase, displacing the mixture of air and fuel ahead of it. When crankcase compression begins, the intake ports are ideally filled with air only and when scavenging starts, the air gets into the combustion chamber downstream of the rich air-fuel mixture. This reduces the scavenging losses and consequentially fuel consumption. Depending on port timing, the intake ports are also filled with residual gas which has a similar stratification effect. Using air for stratification offers a higher potential, since the stratified scavenging with exhaust gas has drawbacks in thermal design and combustion quality due to the residual gas concentration [4]. Both paths, the mixture and pure-air path, are controlled by the piston movement. Also reed valve controlled stratified scavenging engines have been known for a long time [1]. Depending on the manufacturer there is either one single central valve or one for each scavenging port. Since reed valves represent additional moving parts and tend to unspecified opening and closing randomly at high speeds, the piston controlled concept is favoured [4].

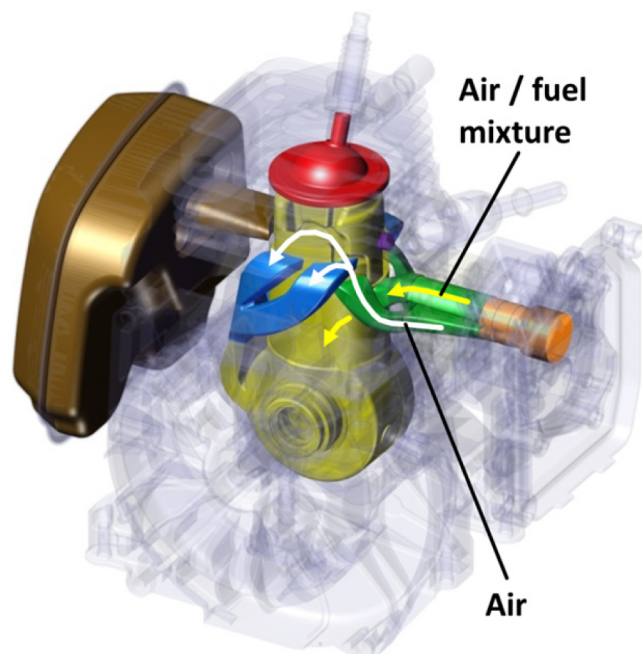


Figure 4. Port configuration

A further big influence on scavenging losses is exhaust port timing. If the exhaust port stays open for a long time, over-scavenging can occur, which means that fresh mixture is transported through the loop scavenging flow field into the exhaust. The higher the intake mass flow the higher are the scavenging losses. This causes the inherent correlation

between specific power and scavenging losses. Hence, HC emissions are higher when the specific power is increased. For this reason emission-optimized two-stroke engines are designed for a reduced delivery ratio in order to achieve a high trapping efficiency for the required power.

Results - Reference Engine

In the following chapter experimental results of the reference engine during WOT (Wide Open Throttle) operation are presented. Figure 5 displays the specific power and the BMEP (Brake Mean Effective Pressure) depending on engine speed. Maximum power is reached at 9.500 rpm; which is why this operating point is used for emission certification. BMEP is increasing at lower engine speeds and reaches 3.3 bar at 6.000 rpm. Both positively influence the working characteristic of the tool. Furthermore, the layout of a decreasing BMEP with higher engine speeds realized by a lower delivery ratio is required for a high trapping efficiency of mixture and a necessary power limitation at 12.500 rpm.

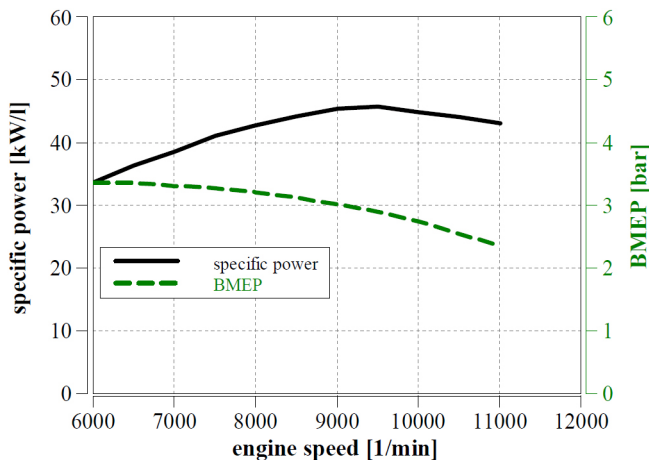


Figure 5. Specific power and BMEP - WOT

The customer demands for high power and quick response of the engine without additional costs. These demands are met by a rich mixture in PL (part load) and WOT operation. Moreover, the rich mixture is additionally cooling the engine and reduces thermal stress. Regarding the shortage of resources and the greenhouse effect, the reduction of fuel consumption is of great interest and therefore an important customer demand. A BSFC (Brake Specific Fuel Consumption) lower than 450 g/kWh is reached between 7.000 and 11.000 rpm and the minimum of 440 g/kWh is achieved at the customer relevant operating range of 9.000 to 9.500 rpm. The BSFC is negatively influenced by the rich mixture ($EQUI > 1$), but a high fuel trapping efficiency up to 96 % caused by stratified scavenging and the fast combustion induced by the intake port geometry enable low fuel consumption.

The CO emission ranges between 240 and 300 g/kWh. In contrary to CO emission, NO_x formation is reduced by the rich mixture. Additionally, high EGR (Exhaust Gas

Recirculation) rates lead to low NO_x formation which results in NO_x emissions of approximately 3 g/kWh over the whole WOT operation area. Due to the fact that two-stroke engines are open systems during scavenging, low HC emissions are a development task of special interest. This engine achieves low HC emissions because of the stratified scavenging process. Generally, HC emissions stay below 45 g/kWh during WOT operation and 22 g/kWh are reached in the emission legislation relevant operating point (9.500 rpm / WOT - Figure 6). This relates to a trapping efficiency of 96 % concerning fuel.

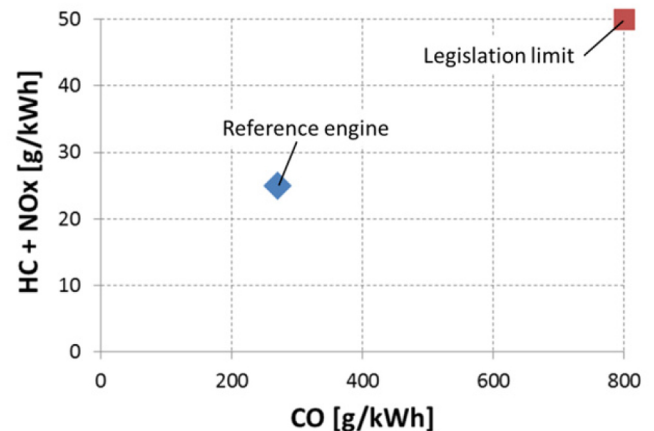


Figure 6. Emissions of the reference engine at 9.500rpm WOT

The stratified scavenging process is designed for high engine speeds. Therefore, the trapping efficiency at "low" engine speeds (approximately 5.000-7.000 rpm) decreases to 90 % due to higher delivery ratio, changed in-cylinder flow and little amount of fuel inside the pure-air intake-port. Figure 7 and Figure 8 display 3D-CFD simulation results of the stratified scavenging process. The equivalence ratio is shown through a section of the cylinder and carburettor. The split-plate inside the single-flow carburettor separates the rich mixture (above) and air (below). Rich mixture is transported to the crank case via the mixture-port and pure air is transported to the top of the scavenging ports during the intake phase (Figure 4 and Figure 7).

In some operating points (low engine speed between 5.000 and 7.000 rpm) the gas dynamics lead to a reverse flow of rich mixture to the air intake. The air-fuel mixture is further aspirated by the pure-air intake-port in the next cycle (Figure 8). This reverse flow contaminates the air used for stratification and therefore increases scavenging losses.

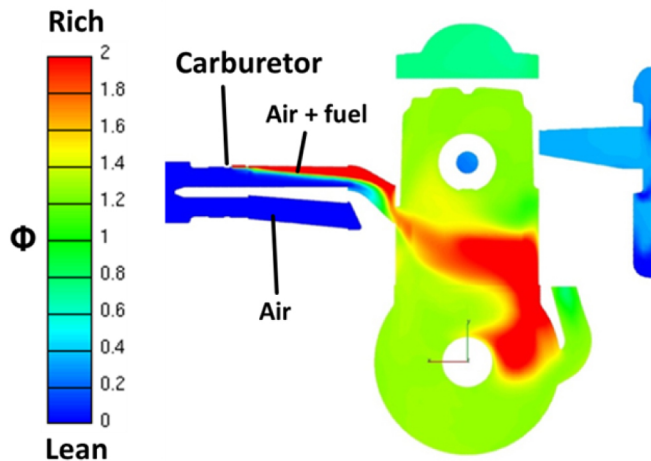


Figure 7. EQUI during intake phase (50°C a. TDC) - CFD result - section through cylinder

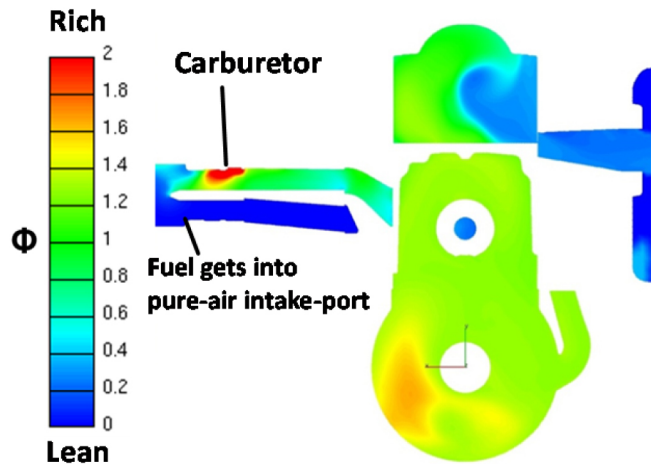


Figure 8. EQUI during scavenging phase (230°C a. TDC) - CFD result - section through cylinder

Conclusion - Stratified Scavenging

A two-stroke engine with stratified scavenging in combination with a carburettor is a cost-effective system featuring low engine-out emissions and low fuel-consumption. However, carburettor systems involve long mixture pathways which can negatively affect the dynamic behaviour and properties of cold-running. Here, injection systems show significantly more variance.

OVERVIEW OF ALTERNATIVE COMBUSTION AND MIXTURE FORMATION SYSTEMS

The main reason for investigations of novel mixture formation systems in combination with two-stroke engines is the further reduction of engine-out emissions (especially HC and NO_x) and the improvement of customer relevant topics.

Low costs are vitally important in this price-sensitive market and therefore the wide range of available injection equipment is preselected regarding its costs. Various mixture formation and combustion systems have been tested by several research groups and organizations. The most promising ones are briefly discussed below in terms of their applicability for future use.

HPDI - High Pressure Direct Injection

Essential progress regarding HPDI for both four-stroke and two-stroke engines has been achieved during the time from World War I to the nineteen-fifties [5, 6, 7]. Two-stroke engine concepts with high specific power (128 kW/l) and low BSFC (260 g/kWh) have been reached [7] and fundamental findings have been investigated [8]. HPDI seems to be the technology that offers the highest potential to reduce scavenging losses. Especially the wide range of possible injection phasing, due to injector position and injection pressure, offers a very high potential to increase fuel trapping efficiency. Several applications of such a system for 50 to 500 cm³ cylinder capacities have been published with analogous results [10, 11, 13]. The trapping efficiency of fuel depends in a high degree on injection phasing. When SOI (Start of Injection) is set after EPC (Exhaust Port Closed) 100 % can be reached. At WOT and especially at higher engine speeds the phasing has to consider the minimum injection time and necessary mixture preparation time for the fuel mass. With presently available injection pressures of 130 bar a late injection is not realizable under all operating conditions and therefore a trapping efficiency of 100 % is not achievable [13]. Investigations at WOT operation with 500 cm³ cylinder displacement showed HC emissions of ~ 20 g/kWh, BSFC of 250 g/kWh and a specific power of over 120 kW/l [12, 13]. Investigations of a 50 cm³ two-stroke engine with direct injection (80 bar) and stratified charge have shown promising results of approximately 18 g/kWh HC emissions at WOT [14]. Generally, the HPDI technology is used in recreation products and has also been investigated for scooters and small engine capacities, but it seems to be too expensive for the application in hand-held power tools.

SDI - Semi Direct Injection

SDI comprises several possible injection positions, sometimes also called indirect injection. The low pressure injector is positioned in the scavenge ports located near to the entry point to the combustion chamber [12, 15, 16]. Therefore mixture stratification should be achieved but the available injection time is limited by the port timing. The use of injectors with a very high flow rate enables the supply of the required fuel mass at WOT but causes problems at idle speed. Due to the limited minimum injection duration of the applied injector technology, too much fuel is injected. Injectors with a well-suited layout for idle operation may have problems to provide the necessary fuel mass at WOT [12]. Therefore some applications are using two injectors [17]. Injection

duration and injection timing are of significant influence on HC emissions. A very short and late injection is preferred to achieve low HC emissions. In WOT operation ~ 40 g/kWh HC emissions have been achieved using SDI in a 64 cm^3 prototype engine for a hand-held power tool [18]. The SDI has high potential concerning hand-held power tool purposes [15, 18], especially as requirements on the injector and fuel system are low.

LPDI - Low Pressure Direct Injection

The potential of the LPDI system for water-cooled 50 cm^3 two-stroke engines has been presented in the past [19]. Utilizing a standard two-stroke engine with an electronic fuel metering and a proper position of the low pressure fuel injector offers a high potential for reducing the scavenge losses for both, full load and part load operation. Nevertheless, LPDI will never reach the high trapping efficiencies of HPDI systems injecting fuel in a closed system [20]. But accounting the aspects of cost and market acceptance, it is a promising alternative to HPDI [21]. Further, cold start emissions as well as scavenging losses and catalyst light-off time can be reduced compared to carburetted engines. Previous investigations with 50 cm^3 LPDI engines have reached low HC emissions of ~ 60 g/kWh, 380 g/kWh BSFC and a specific power of 76 kW/l during WOT [19].

ASDI - Air Assisted Direct Injection

Compressed air is used to support the atomization and vaporization of fuel and to create a stable, easily ignitable air-fuel mixture. ASDI can be independently applied from the scavenging air in order to minimize scavenging losses. Several concepts have been published regarding the pneumatic pressure regeneration using the crank case or an external piston compressor [22, 23, 24, 25, 26]. The essential advantages of ASDI compared to HPDI are the high spray quality, small fuel droplets and low penetration depth achieved with low fuel pressure of approximately 6-8 bar [23]. Additionally, the available range of injection phasing due to the injector position offers a very high potential. A stratification of mixture directly inside the combustion chamber is possible with high evaporation rates, which are advantageous for fuel impingement on the cylinder walls and thereby reduce HC emissions. The results are promising for fulfilling future emission limits - even with small displacements. In WOT operation approximately 10 g/kWh HC emissions have been achieved with a 125 cm^3 engine [24]. Despite the high emission potential, ASDI has not been investigated in the course of this research project focusing on hand-held power tools, due to the additional costs for the sophisticated injector and the compressed air generation.

Overview - Injection Timing

The injection phase and timing of the previously discussed injection systems differ because of inherent

limitations. Mixture formation and scavenging losses are significantly influenced by the injection phase and timing. Figure 9 shows the port timing of the reference engine and the available injection phase of the different mixture formation systems.

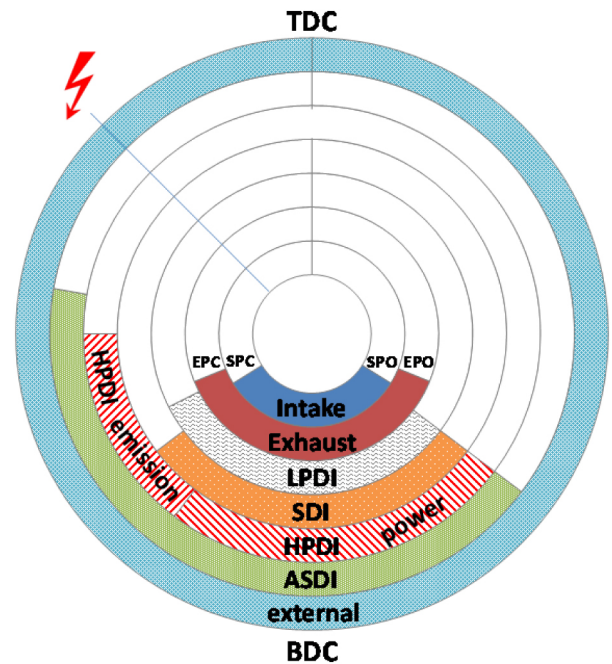


Figure 9. Injection phasing of different concepts

The optimum injection phase using **HPDI** is strongly depending on the port timing, the injection pressure, the spray break-up and the turbulence level in the combustion chamber. When SOI is set after EPC the completely injected fuel can be trapped, but at WOT and especially at higher engine speeds the phasing has to consider the minimum required time for sufficient mixture preparation.

The **SDI** timing is limited by the scavenging port opening (SPO) and closure (SPC). Due to the very short port timing in engines designed for low emissions, the short available injection time is challenging for a sufficient mixture formation.

LPDI can be effected as long as the cylinder pressure is lower than the injection pressure and as long as the injector nozzle is not covered by the piston. Generally, the top limit of the injector position is narrowed by the exhaust port timing as the used low-cost injector cannot resist high cylinder pressure and temperature.

As the **ASDI** has a good atomization of the injected fuel, the injection can occur independently from the scavenging air. Even a very late injection is realizable due to the sophisticated mixture formation and small droplet size.

The **external mixture formation** is spatially separated and therefore the available injection timing is almost not influenced by the port timing.

LPDI, **SDI** and **external mixture formation** (here: **CCI** - crank case injection) are low-cost technologies with high