

Active Air Management with High Speed Flap for DI-Diesel-Engines

Andreas Broda, Marcus Rieping and Peter Eilts

Technische Universität Braunschweig, Institute of Internal Combustion Engines

Alfred Elsäßer and Patric Genieser

MAHLE International GmbH

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ABSTRACT

The paper demonstrates the potentials of a high speed flap installed upstream of the intake valve of a HSDI diesel engine, to control the amount of fresh mixture and its composition. This switching device will not only enable the impulse charging or Miller-Cycle, but also a new method of external EGR.

INTRODUCTION AND BACKGROUND

The modern diesel engine is considered worldwide as a power plant, which combines performance and efficiency. In Western Europe, diesel powered cars have already reached a market-share of about 46% and customers demand is still raising. However stringent emission regulations constrain the manufacturers and research institutes to break new grounds. In addition to a further optimization of combustion chamber geometry and injection systems, new concepts to influence and control the gas exchange process and intake air composition have to be examined. Beside Variable Valve Train systems, which cannot be easily realized at HSDI diesel engines, an impulse charging device represents a low cost alternative with almost the same benefits. Furthermore today's diesel engines in operation can be easier retrofitted with an impulse charging device than with a Variable Valve Train.

IMPULSE CHARGING

The time-varying inlet flow to the cylinder causes expansion waves to be propagated back into the inlet manifold. These expansion waves are reflected at the open end of the manifold (at the plenum) causing positive pressure waves to be propagated towards the cylinder. If the timing of these waves is correctly sequenced, the positive pressure wave will cause the pressure at the inlet valve at the end of the intake process to be raised above the nominal inlet pressure.

This will increase the inducted air mass [1]. The optimal length of the intake manifold l_{opt} is reciprocally proportional to the engine speed n_m (with constant inlet valve timing and a constant speed of sound a).

$$l_{opt} = 10 \cdot \frac{a \text{ [ms}^{-1}\text{]}}{n_m \text{ [rpm]}}$$

The application of an Air Pulse Valve (APV) will use this pressure wave effect independently of the engine speed. In the last decades a number of surveys have been done concerning the impulse charging with different types of Impulse Charge Valves [2-11], but the effects were still the same. As illustrated in the following figure, an APV is placed between a surge tank and the intake valve (IV). It is possible to open and to close the intake cross section within shortest times independently from the intake valve. In this paper the volume between APV and IV will be called chamber.

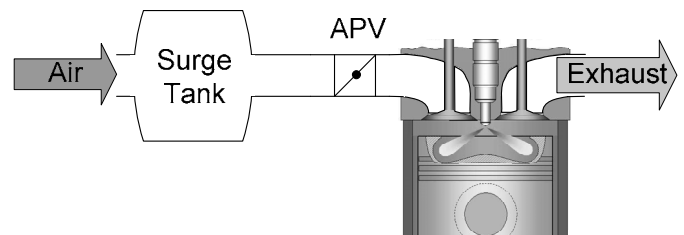


Fig. 1: APV application

The proceeding is as follows:

1. While the engine draws in with an opened intake valve, the APV remains closed. Due to the downward piston stroke, a negative cylinder and chamber pressure occurs.
2. When the opening of the APV starts, air mass will flow with high velocity into the combustion chamber whereas an expansion wave will run from the APV to the surge tank.

3. Because of the characteristic of an open tube, where pressure waves will be reflected with a reverse prefix, a positive pressure wave runs back to the combustion chamber.
4. This wave can be trapped in the cylinder and results in a better filling. If the pressure will not be kept by the intake valve but rather with the APV, a chamber pressure above the nominal value can be achieved. This increase of chamber pressure assists the next gas exchanging process.

MILLER-CYCLE

The Miller-Cycle, presented by R. Miller in 1947, is a low temperature supercharging technique which can be achieved with variable valve timing. The aim was to maintain as much as possible the pressures occurring in the conventional charged engine, but to increase the charge due to higher density generated by intense cooling [12, 13]. The other option of this technique is to maintain the charge of the engine and to receive a lower combustion temperature.

In the Miller system, charge cooling takes place in the engine itself by expansion of the air due to an early intake valve closing. To realize the same charge, the turbocharger has to compensate the filling losses with higher charge pressures. For this purpose it is essential to use a high efficiency charge air cooler to profit from the temperature advantage at increased boost pressure. With this method, the compression work will be shifted from the piston to the turbocharger while cooling between them will take place [14].

If the APV is used for an early closing instead of the engine valve, the leakage of the impulse charger will be the significant factor. An ideal APV of 0% leakage will have a potential similar to a Variable Valve Train.

Derived from this process management, a so called "Miller-Cycle without air mass compensation" is also possible. This process is not suited for high loads, but rather for the lower load ranges, where the air fuel ratio is high enough to reduce the intake opening period. The effects of this mode will result in lower combustion temperature and reduced exhaust gas flow, which is caused by the reduction of the intake mass flow.

OPTIMIZATION OF COLD START BEHAVIOUR / HEAT LOADING

The aim of the so called Heat Loading is, in contrast to the impulse charging, not to increase the cylinder charge, but to increase the charge temperature. A late APV, close to BDC creates an overcritical pressure gradient that causes a flow involving friction. As a result, the energy of the inflowing air mass will be converted into heat and pressure [3]. In addition the turbulence of the charged air increases, which improves the quality of the air fuel mixture. This effect can be used with the first engine revolution. If the effect is high enough, a cold start of a diesel engine can be done without an

assistance system like glow plugs. To reduce the geometric compression ratio with retention of the glow plugs will also be possible.

CYLINDER SELECTIVE EXHAUST GAS RECIRCULATION

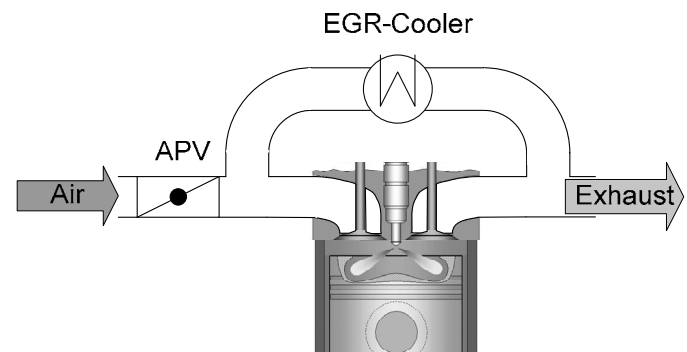


Fig. 2: Exhaust Gas Recirculation with APV

By integration of an APV in each intake port as well as a corresponding EGR line (Fig. 2), it is possible to control the external EGR rate within shortest times. There is not only a positive effect on pumping losses but also on the cycle efficiency. Due to the cylinder selective exhaust gas induction between APV and the intake valve, the necessary negative pressure gradient can be obtained. For this reason a throttling of the exhaust- or the intake-mass-flow can be avoided and pumping losses will be reduced [15]. At cold start conditions, bypassing the EGR cooler will reduce the warm up time better than high pressure EGR-loops, due to a shorter EGR-line.

SWIRL OPTIMIZATION

With a late intake opening via the APV or a short closing within the intake stroke, a higher flow velocity of the intake air can be generated and optimized for all speed ranges. Due to the small bores of passenger car engine cylinders, a speed adapted swirl ratio assists the air fuel mixing and therefore the combustion process. By using this technique, a swirl flap can be avoided.

SMOOTH ENGINE SHUTDOWN

To minimize vibration and harshness of a diesel engine shutdown, it is necessary to influence the effective compression ratio and to lower it as far as possible. The different methods can be differentiated into internal and external cylinder techniques. In-cylinder techniques have decompression valves or variable valve actuation systems that allow late intake closing. It is also possible to lower the effective compression by the reduction of the manifold pressure. The method using a throttle, like SI engines do, is state of the art [16]. While using one APV per cylinder, this function can be disabled. This way the effect occurs much faster, since the volume between APV and IV is quite smaller than between throttle and IV. Furthermore, throttling with an APV is much more efficient due to less leakage.

ENGINE BRAKE FOR HD-TRUCK-APPLICATIONS

The exhaust brake of a heavy duty truck engine (realized with an exhaust throttle or a pressure resistant VG turbocharger) can be intensified with the application of an Air Pulse Valve per cylinder. During the intake stroke up to the bottom dead center, a closed APV results in a maximum of suction work. In order to diminish the negative pressure, the APV must be opened in BDC, so that the spent expansion work cannot be retrieved in the compression stroke.

NEW COMBUSTION PROCESSES

The Homogeneous Diesel Combustion (HDC) and all of its derivatives will only be possible in transient cycles if air and/or exhaust gas mass can be metered precisely beside the accurate injecting control. The dynamic control of the exhaust gas mass as well as the combustion temperature represents the key function for a series application of HDC in passenger car diesel engines. Using an APV in conjunction with a direct injection homogeneous combustion process creates the following benefits:

- Controlling the start of combustion not only by the EGR rate, but with an active temperature management realized by different types of Miller-Cycles
- Better homogenization of the air fuel mixture by high inlet swirl at lowest speeds. Less THC emissions due to a swirl adaption of the injection jet length so that less wall impingement occurs.
- Combustion optimization, due to a charge/exhaust gas stratification.
- Cylinder- and cycle-selective control of the explained strategies.

EXPERIMENTAL SETUP

TEST ENGINE

The experimental engine is a modified 4-cylinder Diesel engine with common rail direct injection system and four valves per cylinder. The technical specifications of the engine are listed in table 1. The engine has been rebuilt for a 1+3-mode, because only the fourth cylinder was used for the experiments. As the following illustration shows, all flows from and to the 4th Cylinder are separated from the others. It is possible to supercharge cylinder 4 with a VG turbocharger, which is fed by cylinder 1-3. Beside a separate injection system that consists of a BOSCH CP1 high pressure pump, a series CRIP1-injector and a specially developed ECU, cylinder 4 possesses an independent exhaust gas line.

Single-Cyl. Displacement [cm ³]	537
Bore [mm]	88
Stroke [mm]	88.4
Compression Ratio [-]	18:1
Valves per Cyl. / Number of IV	4 / 2
Ø-IV / Ø-EV [mm ²]	30.2 / 28.4
Intake Valve Opening [°CA ATDCL @ 0mm]	-25
Intake Valve Closing [°CA ABDCH @ 0mm]	57

Table 1: Engine Specifications

For the analysis of dynamic pulse charging, a surge tank is integrated into the intake system upstream of the APV to make the reflection of negative pressure waves possible.

The indication system used was a Combi from SmeTEC with a SmeTEC crank angle encoder. Cylinder, intake pressure before and after the impulse charge valve, as well as exhaust pressure of cylinder 4 were indicated. Furthermore the injection control, the injection pressure and APV position were recorded. For the fourth cylinder, the fuel mass was measured with a Massflo from Siemens and the airflow was quantified with a Sensyflow from ABB. The gaseous components were measured with an EXSA 1500 analyzer cabinet from Horiba, PM emissions with an AVL Smokemeter 415. Due to the short mixing section between intake and EGR-valve, which could cause incorrect CO₂-measurements, the EGR-rate is calculated by the measured flow rate in these experiments.

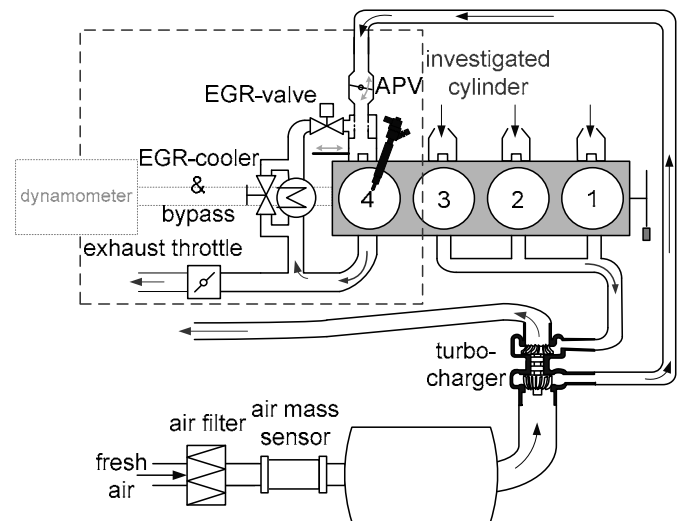


Fig. 3: Test Engine Setup

EXHAUST GAS RECIRCULATION SETUP

To realize EGR, exhaust gas is extracted directly after the exhaust valve and fed to the EGR valve via an EGR cooler, which can be bypassed to use hot EGR. The EGR valve is connected to an EGR-mixer-module, so that the exhaust gas is homogeneously entering the intake air. The following two figures show two different installation configurations. In configuration "A" the exhaust gas is admitted between APV and intake valve,

configuration “B” is based on the exhaust gas feeding upstream the APV (the pictures show the prior actuator design).

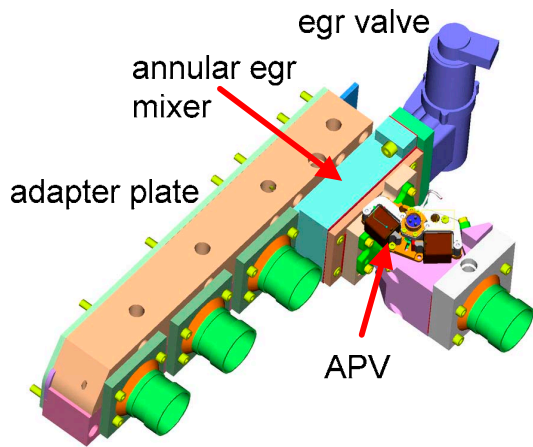


Fig. 4: EGR configuration “A”

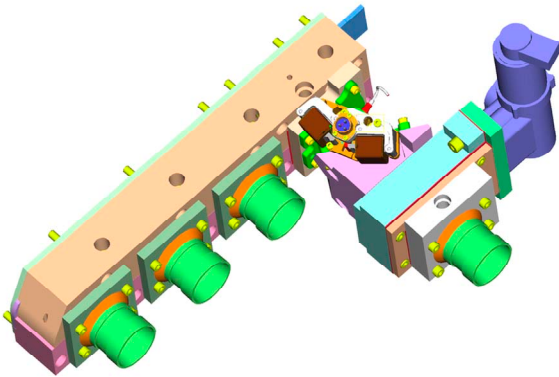


Fig. 5: EGR configuration “B”

AIR PULSE VALVE

The Air Pulse Valve (APV) was developed by MAHLE International GmbH to realize impulse charging of SI engines (explained above). This can only be achieved with a maximum opening cross section within minimal switching time. In order to fulfill this requirement a flap-system with an electromagnetic drive was chosen. The following illustration shows the structure of an air pulse valve in principle. An electromagnetic actuator exerts a momentum on the hollow shaft, which is positive locked with a torsion bar. The hollow shaft is pivot-mounted in a special housing and a carbon fiber reinforced plastic flap is connected with it.

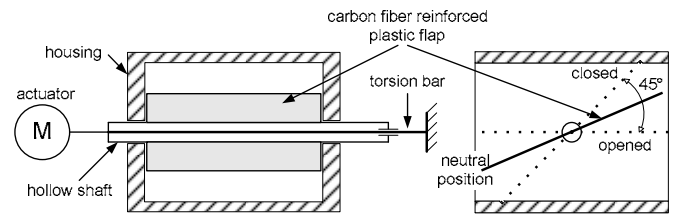


Fig. 6: Structure of an Air Pulse Valve

The drive mechanism is based on an electromagnetic spring-mass-actuator. The actuator design represents the advancement of a typical spring-mass actuator which consists of two magnets and a torsion bar. The actual system consists of four field coils connected in series. This configuration allows moving the armature by means of magnetic force from the neutral position to an end-position without using the spring-mass-actuator typical oscillation method. The armature shaft is of a hollow shaft design that enables a space-saving integration of the torsion bar.

The tightness of the flap system in the closed condition is the crucial factor for the realization of the charging effect. The APV that was provided by MAHLE had a maximum leakage of $V_L=0.24 \text{ m}^3/\text{h}$ at $\Delta p=60\text{kPa}$. For comparison an actual EGR-valve has a leakage up to $V_L=0.6 \text{ m}^3/\text{h}$ at $\Delta p=60\text{kPa}$ [19].

The opening cross section is 1300mm^2 , which corresponds approximately to the cross section area of both intake valves, so that no flow losses due to the actuator will occur within the intake port. The supply voltage is about 14V. The table below shows the power consumption at different operation modes.



Fig. 7: Air Pulse Valve (APV) of the latest generation