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**A felsőoktatás minőségének javítása kiválósági központok fejlesztésére alapozva a Miskolci Egyetem stratégiai kutatási területein (TÁMOP-4.2.1.B-10/2/KONV-2010-0001)**

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**Challenges of Engine Downsizing**

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## 1 INTRODUCTION

Engine downsizing – as the term applies - is quite simple: replace a bigger engine with a smaller one that produces the same power output with lower fuel consumption and less harmful emissions. To take a closer, more scientific look the downsized engine needs to have lower swept volume of fewer cylinders compared to engines currently in production. Fewer cylinders pump less air and fuel mixture hence producing less pollutant. These serve fuel economy and lower $CO_2$ emission. The main problem here is how to produce a vehicle that fulfils the ever stringent emission legislations and fuel consumption requirements with performance parameters that still satisfy the possible end user. Solutions derived for diesel and petrol engines differ slightly but when vehicle mass has to be kept at minimum, Otto-engines are the primary choice of the designer. Now let us see the collection of details on how the above goals can be achieved and what areas can be improved upon by future work.

## 2 GASOLINE DIRECT INJECTION (GDI) AND STRATIFIED CHARGING

During the combustion in an Otto engine an air-fuel mixture is burnt. The mixture has to be produced before combustion is started by the spark at the spark plug. In the past carburettors served this purpose but with advancements in technology first Indirect Fuel Injection (IFI) then Direct Fuel Injection (DFI) has been developed. In this latter case the fuel injector is placed in the cylinder and injects fuel during the compression stroke where it evaporates. The specific position of the injector or in cylinder air movement or the specially shaped piston crown prevents the formation of a homogenous cylinder charge and assists the injected fuel to reach the spark gap by the end of compression stroke (Fig. 1.).

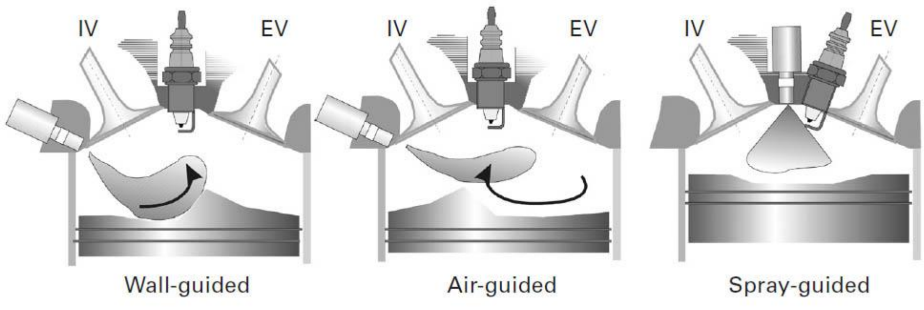


Figure 1
Different type of GDI combustion concepts (Zhao [1])

By the time ignition takes place a cloud of easily ignitable fuel rich mixture surrounds the spark plug, while the remaining space consist much less, if any, fuel. The average fuel content across the combustion chamber is way below stoichiometric, resulting in lambda values in the range of 1.6-2 while improving fuel efficiency and decreasing $CO_2$

emission. It also has a side effect that the isentropic exponent will be closer to pure air (Zhao [1], also see Section 3). The down side of the process is that excess air is present during the burn process and the exhaust gas contains considerable amount of NOx emission that requires a three way catalyst to be employed (Leduc *et al* [2]).

## 3 IMPROVING THERMAL EFFICIENCY

According to Fülöp [3] the theoretical thermal efficiency of an Otto engine is defined by the following formula:

$$\eta = 1 - \frac{1}{\varepsilon^{\kappa-1}} \tag{1}$$

where:

- $\eta$: thermal efficiency
- $\varepsilon$: compression ratio of an engine
- $\kappa$: isentropic exponent (for air $\kappa$=1,4)

As can be seen either raising the compression ratio or the isentropic exponent improves thermal efficiency. However raising compression ratio has an upper limit. At a fuel specific compression ratio, due to the heat generated during the compression stroke, the fuel starts to burn spontaneously, rapidly raising the pressure in the combustion chamber. This type of combustion is called knock or detonation and is detrimental to the engine. In GDI engines the onset of detonation can be mitigated by the latent heat of the evaporating fuel that decreases the temperature of the compression process (Zhao [1]). To cool the charge to be burnt, excessively retarded (compared to normal) closing of intake valves can be used (Atkinson cycle). The same goal can be achieved by the Miller cycle where the intake valves are closed before the intake stroke finishes. Both solution reduce the mass to be compressed and lowers the charge temperature. In turbo charged applications cooled exhaust gas recirculation (EGR) can also be exploited to lower the temperature of the air-fuel mixture before ignition. This way the tendency to detonate is reduced (Loveday [4]).

Quite the opposite philosophy is to design an engine to operate in the autoignition zone. The roots date back to 1995 when Honda achieved great sporting success with its two stroke EXP-2 trail motorcycle that ran in Controlled Autoigintion (CAI) mode at part load conditions. The same principle adapted to modern GDI engines using extreme lean or EGR diluted air-fuel mixtures produce very low CH, CO and NOx emissions while deliver improvements in fuel economy.

Figure 2
Honda EXP-2 motorcycle with two stroke engine that used CAI at part load running

## 4 IMPROVING MECHANICAL EFFICIENCY

At partial load conditions frictional losses and friction generated heat loss account approximately 25% of the total heat energy of the fuel. As Knopf [5] states four or, if we think in extremes, three cylinders also produce less friction with fewer mechanical parts than a five or six cylinder unit. Hence frictional losses are decreased together with the unit mass of the engine.

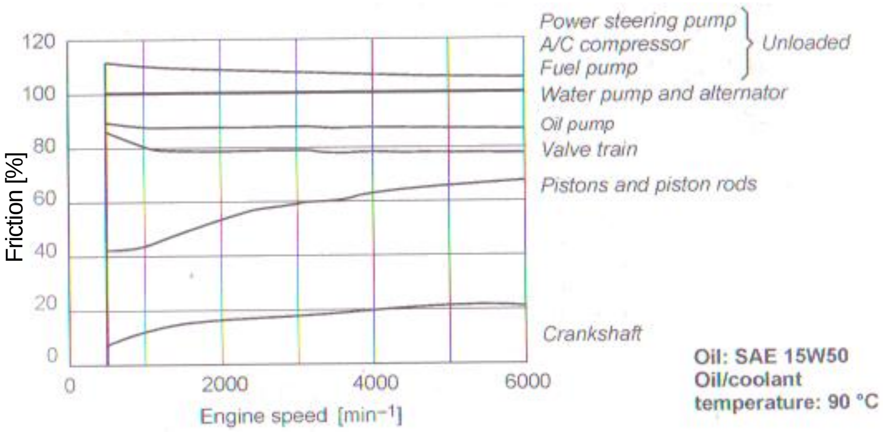


Figure 3
Percentage of different sources of friction in a SI four stroke car engine
(from Basshuysen [6])

Using light weight pistons made of steel and titanium connecting rods also decrease mechanical losses due to the decreased inertia forces that generate friction. Light weight parts provide better driving dynamics as well, which is important since consumers still want to drive performance vehicles. Cylinder arrangement and firing order have their influence on the number of parts an engine is built of. Due to the nature and amplitude of out of balance forces one design may need additional balancing shafts with all the parts that generate friction while another design lives happily without them. Balancing devices may contribute 18% of the total friction of an engine (Basshuysen [6]). Electromagnetic powertrain mounts may also be used to iron out the vibrations from an engine that has no inner balancing device to cut on mechanical losses while maintaining occupant comfort. In the search for lower friction, surface coatings play a significant role. According to Wang [7] valve train friction contributes around 18% of the total friction of an engine. As Schommers [8] states sliding contact of a cam and follower benefits a very hard diamond like carbon (DLC) coating while the pistons thrust face may be coated by $MoS_2$ or anti-friction polymer coatings while piston rings may use Mo or TiN coating with lower tangential force. To cut mechanical losses especially at low engine temperatures low viscosity oils are used or oil heating is required. All metal-metal contact faces maybe aided by isotropic super finish (ISF) that produces a very smooth surface with improved load bearing capabilities that has superior lubricant retention characteristic therefore less power is lost due to frictional losses (Winkelmann [9]). To increase mechanical efficiency of an engine there is the possibility to use rolling bearing elements instead of plain bearings. The advantage is that the oil pump needs to supply less lubricant at lower pressure that reduces the power requirement of the pump hence improving the overall efficiency of the engine. Reducing the diameter of plain bearings favourably affects friction losses, too.

## 5 VALVE TRAIN ISSUES

To get acceptable power level from downsized engines with good drive quality valve opening and closing points must be timed according to engine operating conditions. With mechanically driven valves it is achieved by varying the position of the camshaft relative to the crank shaft by the combination of electric, hydraulic, and mechanical devices or motors. In some constructions, e.g. BMW Valvetronic (Fig. 4) valve lift is also simultaneously adjusted to load conditions while other manufacturers use different cam lobes or valve deactivation devices for low and high load running.

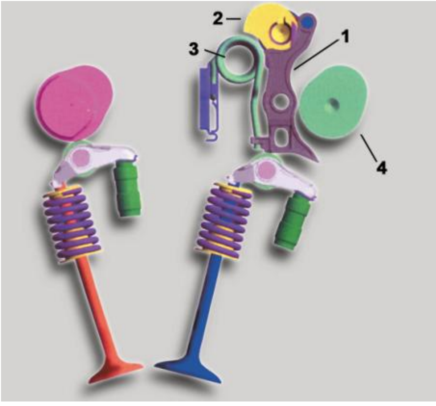


Figure 4
BMW Valvetronic system main components
1: Intermediate lever, 2: Eccentric shaft, 3: Returning spring, 4: Intake camshaft

Using variable timing and lift fuel consumption can be reduced as much as 15%. However these devices increase the complexity of the engine and still impose an rpm limit which also limits the achievable power density of a given engine. As the valves remain seated to their seats by one or two springs, the spring with the mass moving together with the valve creates an oscillating system. This resonates at certain engine speeds and causes the valves to lose contact with the control mechanism and smash into the piston or into their own seats with detrimental effects.

## 6 VOLUMETRIC EFFICIENCY

To provide high power level from a small engine requires highly efficient gas exchange process. Due to constraints mentioned in Section 3 an engine that is efficient in part load conditions will suffer at high rpm, high load condition and vice versa. To overcome the problems some means of supercharging can be exploited. Either roots/screw type chargers or turbine driven compressors can be used though using turbo supercharging recovers some of the heat energy lost in the exhaust flow. The ultimate solution to the conflicting engine parameters that produce efficient running at both low and high speed is to apply a twin turbocharger arrangement. Turbochargers can be combined with electric motors as well, to produce an electrically driven turbo or an electric-turbo compound engine. Even though it is an effective way to create an engine with high efficiency the cost penalty must be paid. One cause of the inefficiencies in the system is the valve itself: the gas flow is directed through a port with sudden flow path changes. Moreover the port cross sectional area is constantly changing during the opening period reaching its maximum aperture only for a fraction of a moment. This can be translated into a varying degree of choking of that particular port which deteriorates the useful effects of pressure wave pulses present in the exhaust or intake tracts. Thermodynamically poppet valve engines must also make a compromise between efficient combustion chamber shape and suitably sized valves with adequate flow capability. To reach a given performance level, the four valve arrangement proved to be the best compromise but the space required by the valves in the cylinder head reduces the squish area. The squish band is placed around the piston circumference. When the piston reaches TDC the squish band is closed and fresh charge sitting in the far extremes of the combustion chamber is squeezed into the main gallery of the combustion chamber just before ignition. This type of movement enhances the burn of greater amounts air fuel mixture in the main combustion event and greatly improves combustion efficiency, fuel consumption and reduces the tendency of knock without sacrificing cylinder filling. By positioning the intake ports asymmetrically to the valve stem axis the intake charge can be forced into a swirling motion. Another important aspect is the tumbling motion of the fresh mixture within the cylinder. It is induced by the inclination of the intake port, with shallower angles producing greater tumble but sacrificing volumetric efficiency. Swirl is a rotational motion of the fresh charge around the cylinder symmetry axis, while tumbling motion takes place around an axis that is perpendicular to the symmetry plane of the cylinder (Fig. 5). From the two charge movements induced during the intake stroke tumble preserves its energy to a higher extent by the ignition. Together with the piston crown and combustion chamber design these effects can be used to create the air movement necessary for a successful GDI fuel system.

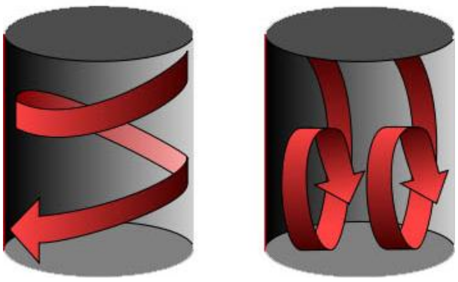

Figure 5
Difference between swirling and tumbling motion of the fresh charge in the cylinder (Wikipedia)

## 7 FUTURE WORK

As can be seen from the above sections a lot of effort has been made to improve the efficiency of the Otto cycle engine. From these, issues relating to the valve train and volumetric efficiency show cost effective improvements for the future. To obtain the benefits of a highly efficient engine without the need of a turbocharger, that adds complexity and cost to any design, the following areas need to be refined:

- Reduced flow losses
- Reduced power requirement to operate valves and valve gear
- The value of the force to open the exhaust valve should be independent of the combustion chamber pressure
- Possibility to apply greater ports to improve volumetric efficiency
- Higher possible maximum engine rpm
- Greater squish area to improve thermal efficiency
- Piston face without valve pockets to improve combustion efficiency and reduce the formation of HC emission

– Higher tumble ratio due to the positioning and flow pattern of the valve
– Higher combustion speed due to increased squish and tumbling action

These conflicting requirements may be fulfilled with poppet valve engines but greater scope exists for unconventional valve systems. Our research program is aimed on an arrangement where the intake and exhaust ports are uncovered by a fully or partially rotating assembly. This special solution will not only eliminate the problems associated with poppet valves but may open up unconventional engine management strategies and even higher power levels from downsized engines, too. Project results will include a comparative validation of a special valve arrangement and a poppet valve system by the means of CFD and 1D engine simulations.

## 8 ACKNOWLEDGEMENT

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