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# THE Z ENGINE, A NEW TYPE OF CAR DIESEL ENGINE HAVING LOW EMISSIONS, HIGH PART LOAD EFFICIENCY AND POWER DENSITY AND LOW MANUFACTURING COSTS

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## ABSTRACT

From 1990 to 2000 many car manufacturers and research companies searched for ways of improving the 2-stroke car diesel engine. The aim was to produce a lighter, smaller and more economical engine. Some remaining problems, such as HC emissions and excessive piston ring wear, prevented the introduction of the 2-stroke diesel engines in modern road vehicles.

In 1999, Aumet Oy began to research a 2-stroke car diesel engine, called the Z engine, in co-operation with the Internal Combustion Engine Laboratory at the Helsinki University of Technology (HUT) and the Energy Technology Department at the Lappeenranta University of Technology (LUT). So far, three master’s theses, two SAE Papers and one Fisita Paper have been completed on the subject. Modern simulation tools, such as Star CD, GT-Power and Diesel RK have been used . Aumet’s research project was a part of the Finnish Engine Technology Programme, ProMotor, and it was supported by the National Technology Agency Finland, TEKES. A prototype engine made its first start in December 2003 and the testing of the engine has been made three years in a test bench at VTT (Technical Research Centre of Finland). The Z engine has got until now five international patents, several are pending and Euro patent is expected to get before summer 2008.

The Z engine introduces a completely new work cycle. It combines the best parts of 2- and 4-stroke engines. In the Z engine, work is produced at every crankshaft revolution as in 2-stroke engines. The Z engine does not have 2-stroke type scavenging or its disadvantages: mixing of the new charge with the exhaust gas or the loss of the scavenging gas to the exhaust channel. The Z engine uses poppet valves, so there are no problems with the wear of the piston rings and the emissions caused by lubricants. Thus, it is possible to halve the number of the working cylinders of the engine by having one integrated compressor cylinder in the engine. In engines, size of car engines, the piston compressor has a better efficiency than rotating blowers, for example Roots blower and it is also more economical to produce. The turbocharger lowers the volume of the compressor cylinder by 50-70%. A 2-cylinder Z engine is equal to a 4-cylinder 4-stroke engine in its power output and balancing.

In the Z engine, it is possible to utilize the combined high swirl Z combustion with a controlled homogenous charge compression ignition combustion (HCCI). The Z engine has the potential to comply with future environmental legislation without expensive exhaust gas after-treatment.

By using the Z engine it is possible to reduce the manufacturing costs of the vehicles. All the components used in the Z engine are like those used in normal engines and compressors. For this reason, there is no need for many changes in the component supply chain. It is possible to have a diesel car without a $NO_x$ catalyst, when using the Z engine.

# TECHNICAL PAPER

The Z engine contains several new features. It is a combination of a 4-stroke and a 2-stroke engine. The intake and the exhaust poppet valves are placed into the cylinder head. The Z engine doesn't have similarities with 2-stroke engines. There is no mixing of the new charge with exhaust gas or loss of fresh air to the exhaust channel. Because the Z engine doesn't utilize port scavenging, there are no emissions caused by lubricants getting into the cylinder from the scavenging ports and no excessive wear of the piston ring.

The main principle of the Z engine is removing a part of the compression from the work cylinder to an external compressor(s). The external compression is done by a 2-stage compressor set. The first-stage compressor is a turbo charger. The second-stage compressor is a piston compressor that is integrated into the engine. There is an adjustable intercooler after each compressor stage for temperature control. The intercooling is adjusted by using bypass valves. The pressure after the external compression varies from 7 bar to 15 bar.

The combustion air is conducted into the work cylinder through the poppet valves. The intake begins while the piston is approaching the top dead centre (for example around 60° BTDC) and the intake valves are open only about 20° on the crankshaft. This fast intake is possible because of the high intake manifold pressure. The final compression takes place in the work cylinder. The fuel is injected into the cylinder. The combustion is followed by the expansion stroke. The exhaust valves are opened before the bottom dead centre as in the 4-stroke engines. During the upward stroke, the piston pushes most of the combustion products out from the cylinder until the exhaust closes and the intake opens. Thus an intern EGR is possible.

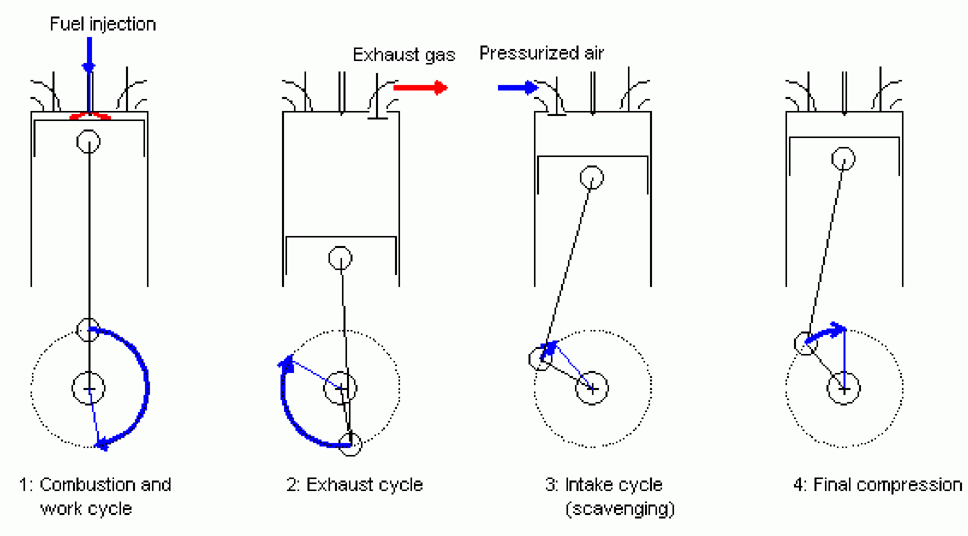

Figure 1: The process in the work cylinder

The geometric compression ratio does not define the maximum compression temperature and pressure in the Z engine. Rather, it defines the maximum power by fixing the compression volume. The compression volume with the maximum allowed pressure and the minimum possible (auto ignition, etc.) temperature gives the mass of the combustion air and thereby defines the maximum power output. The geometric compression ratio is, for example 15, depending on the application.

Because a part of the compression occurs externally, the final compression temperature and pressure are not tied together in the Z engine. This gives the engine designer more parameters with which to optimize the engine for different load, speed and environment situations. The amount of the charge air can be altered by changing the valve timing and by controlling the intake temperature and pressure. This makes it possible to control, for example, the air/fuel equivalence ratio in a compression ignition engine. The valve timing affects the portion of the compression done in the work cylinder and also to the internal EGR.  It is useful to shift more compression to the work cylinder for example at part loads.

The Z engine can also utilize the Otto cycle. The knock phenomenon found at high geometrical compression ratios and pressures when using gasoline fuel can be avoided, because the compression temperature can be controlled separately. A higher overall efficiency could be gained because of the higher compression ratio and better controllability especially at part loads.

## THE HIGH SWIRL Z COMBUSTION

The high intake pressure enables this new combustion method in the Z engine. The maximum transient speed of the intake air coming into the cylinder is over 500 m/s depending on the intake pressure and the valve geometry. By directing this high-speed air tangentially into the cylinder, a very high swirl can be achieved. The swirl number of the new charge can be, for example, 20. The turbulence energy in the cylinder is very high, about ten times higher than in the common diesel engines due to the high intake velocity.

A schematic picture of the intake valve of the Z combustion system can be seen in Figure 2. The flow is held back in a certain sector of the valve to prevent the air flowing backwards into the swirl. Shrouds are used in the figure for this purpose, but some other methods have been utilized in the prototype engine and in future developments. To enable a supersonic flow, the valve is designed to form a Laval-type narrowing/widening nozzle while it is open.

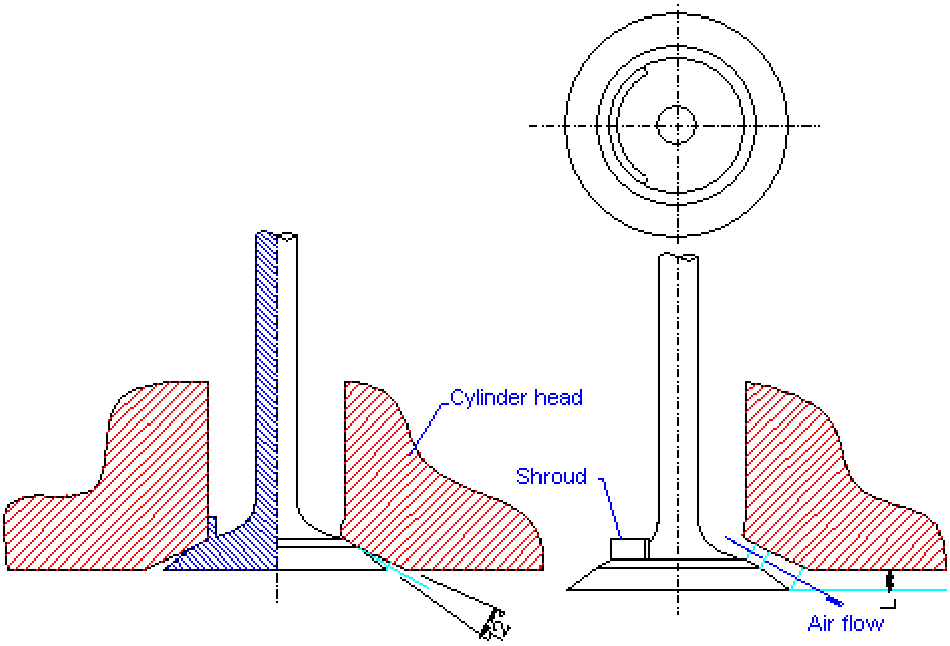

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Figure 2: Valve design

The theoretical flow behaviour in the valves can be seen in Figure 3 The pressure difference has been received from a simulation of the engine. The required ratio between the exit area of the valves and the throat (at the inner seat) area has been calculated from the flow speed and the specific volume of the flow. The calculated exit area/throat area ratio has been calculated from the valve lift data and the valve dimensions. The intern exhaust gas re circulation (EGR) rate was 20% and the exhaust gas was not rotating at the beginning of the gas exchange.

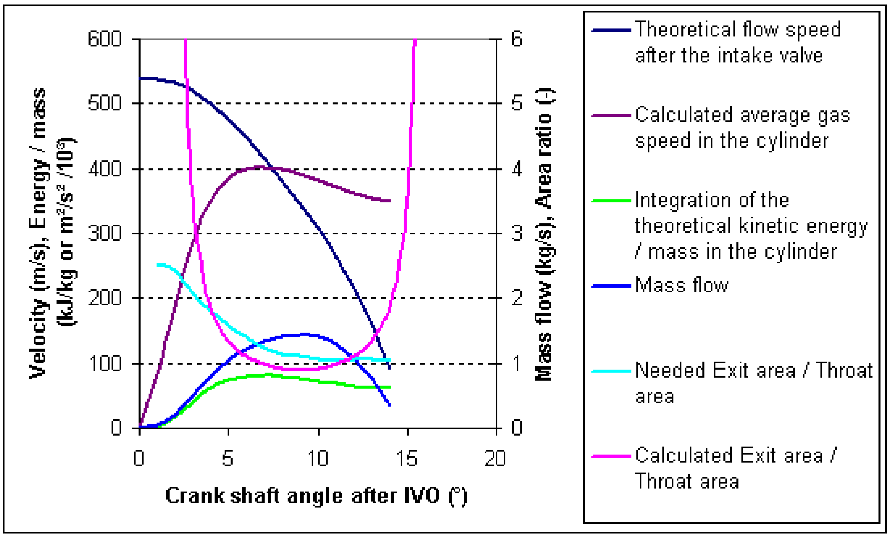


Figure 3: The theoretical valve flow

Figure 4: The heat insulated combustion chamber

The fuel injector can have a hollow cone shape, forming a pintle nozzle injector like that used in gasoline injection systems. This type of injector has been used also in the swirl-chamber diesel-combustion systems. For example, the CAV Microjector, Figure 5, is an injector of this type, which was used in some USA-made swirl-chamber engines in the 80s. These injectors have good atomisation without needing a high fuel pressure. This makes the fuel injection system easier to manufacture and more cost effective. This kind of nozzle has no sac volume and there are no hydrocarbon emissions caused by fuel evaporation from the sac volume. The low injection pressure, only 500 bar, increases the efficiency of the engine by 1,5-2% compared to engines using 1600-2000 bar.

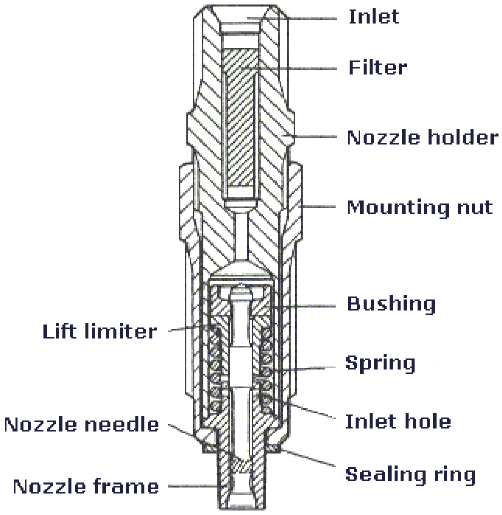


Figure 5: CAV Microjector injector

The NOx measurements of the Z combustion was in made December 2006 at VTT laboratory in Finland. At part load NOx was 0,8 g/kWh and the efficiency was 35%.
In order to reduce still NOx, it was further developed a new type of combustion, a combination of Z combustion and late HCCI combustion. The fuel injection of the HCCI combustion occurs at about 60° BTDC, when the temperature is about 700K and the pressure is about 2-3 bar. This rapid transient area in the gas exchange of the Z engine makes a very rapid evaporation of the droplets possible. The fuel injection to the hot, heat insulated combustion chamber at 5° ATDC ignites the HCCI mixture at 10° ATDC. Enclosed the temperature- and pressure curves between 80°-40° BTDC.

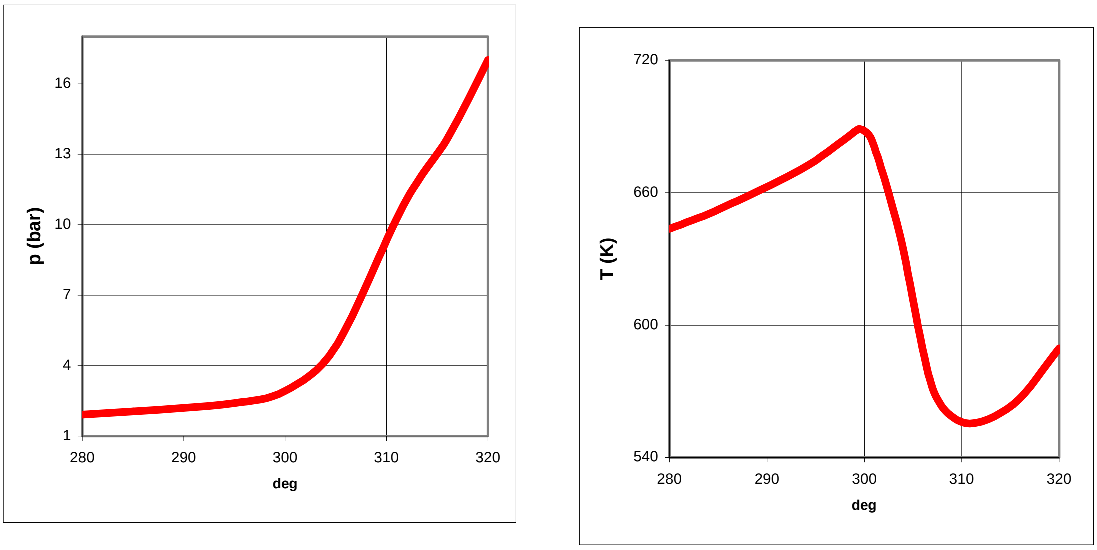
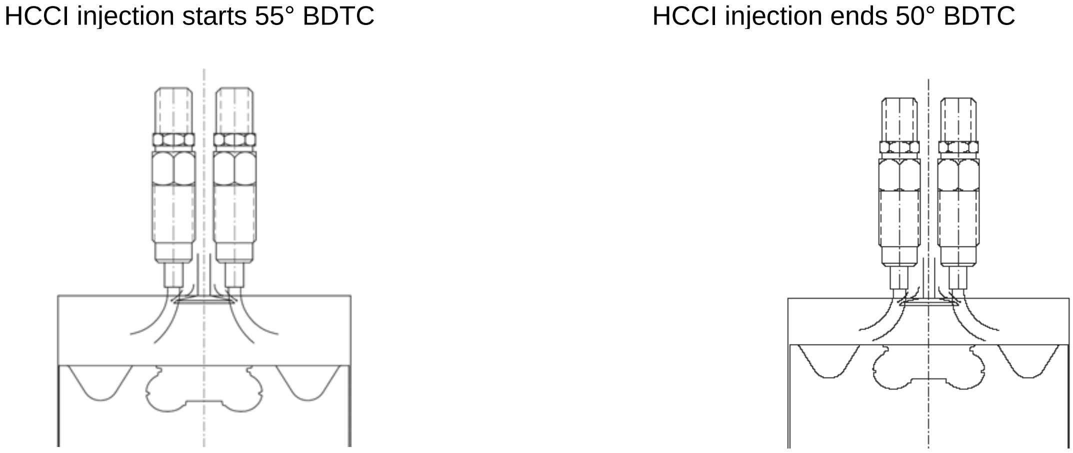


Figure 6: The temperature- and pressure curves between 80°-40° BTD

Enclosed picture of the HCCI injection

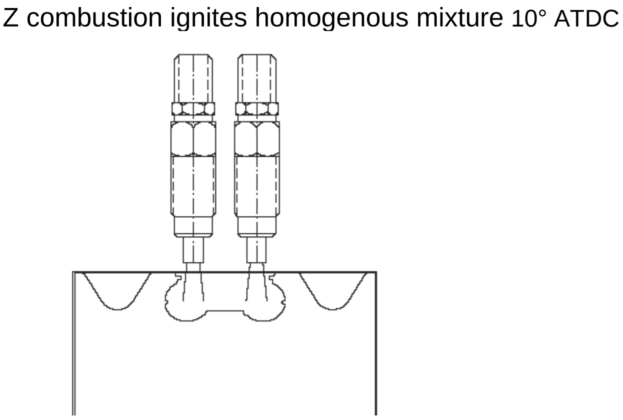


HCCI injection starts 55° BDTC

HCCI injection ends 50° BDTC

Figure 7: The HCCI injection

Enclosed picture of the Z injection



Z combustion ignites homogenous mixture 10° ATDC

Figure 8: The Z injection

Enclosed the piston of the new Z-HCCI combustion

Figure 9: The new piston

The combined Z-HCCI –combustion makes a late HCCI-combustion possible, as the compression temperature at TDC do not exceed 800 K and thus the HCCI mixture don't self ignite. By this way it is possible to trigger the ignition of the HCCI-mixture at 10° ATDC. From this point the down wards moving piston lowers the pressure- and temperature rise during the HCCI-combustion. The slow Z-combustion acts as a pneumatic dumper during the HCCI-combustion. Enclosed the comparison between the split-combustion and the Z-HCCI-combustion

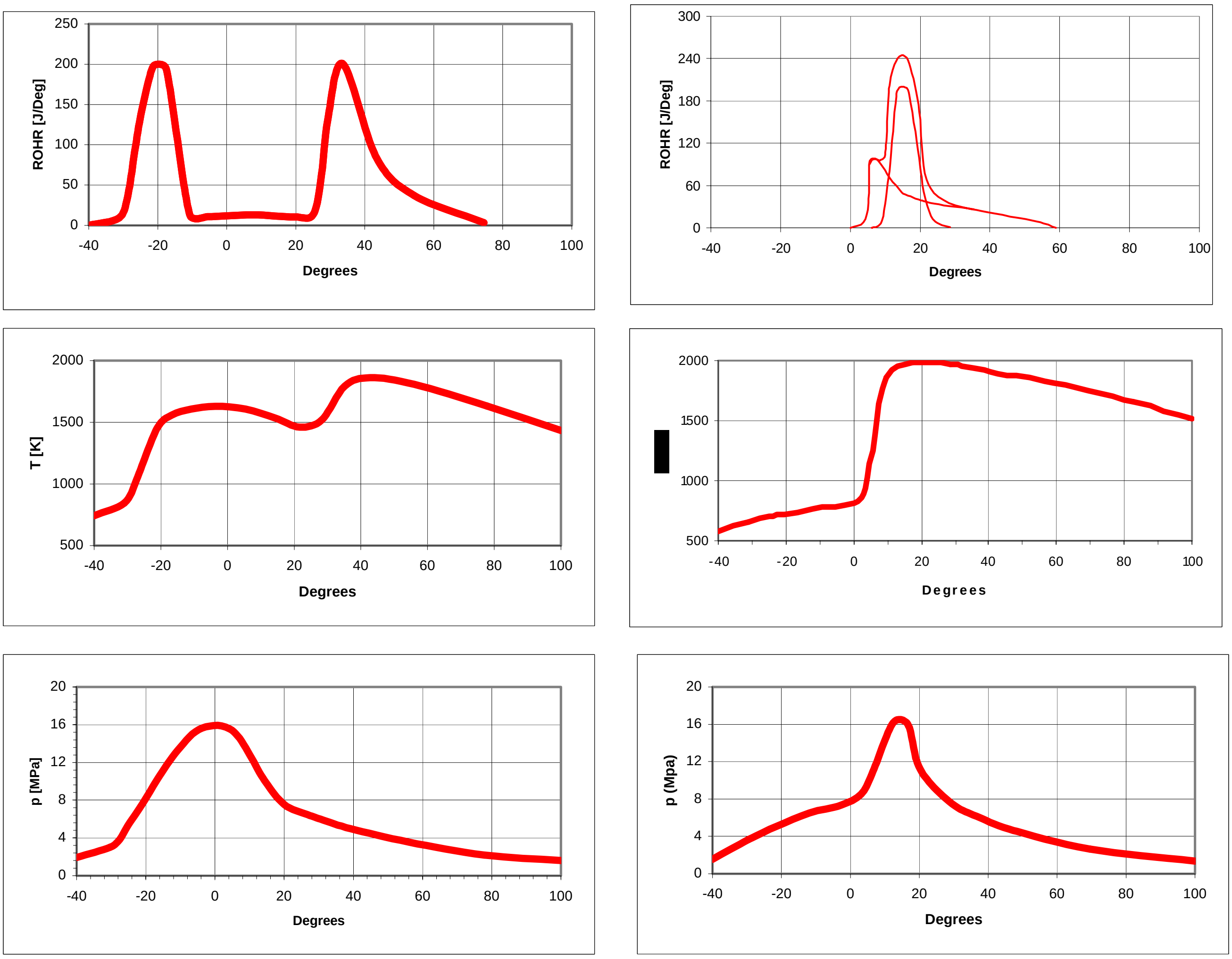


Figure 10: Comparison of Split-combustion and Z-HCCI-combustion

In order to enhance the air-fuel vapour mixing, the piston is equipped with three ribs to brake down the high swirl at TDC and to convert it to a high turbulence. This lowers the heat losses close to TDC during the HCCI-combustion. The high swirl stays anyhow in the heat insulated Z-combustion chamber in the middle of the piston.

Compared with the Split-combustion, the combined Z-HCCI-combustion offers following advantages:

- higher efficiency
- lower heath losses
- better mechanical efficiency
- lower EGR, 20%
- work at every piston stroke in the Z-engine
- higher BMEP

- easy ignition control of the HCCI-combustion
- late HCCI-combustion possible
- very low NOx in the HCCI combustion
- low NOx in the Z-combustion (deNOx phenomena)
- low injection pressure, 200 – 300 bar
- injection rate at part load 95/5
- injection rate at full load 70/30
- NOx at full load 0,25 g/kWh
- NOx at part load 0,05 g/kWh

The test of this new combustion system shall be performed during summer 2008 at VTT in Finland. The combustion system has been simulated with Diesel RK.

## Z-ENGINE, AN ECONOMICAL ALTERNATIVE TO A HYBRID SYSTEM

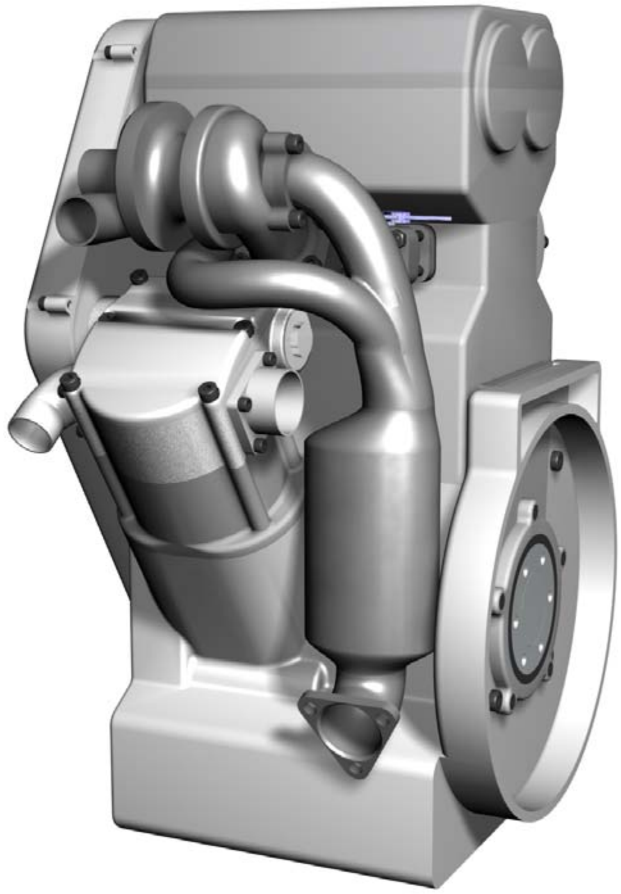


Figure 11: The Z-engine, 2-cyl, 1 l, 100 kW / 4000 rpm

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By using the Z engine, it is possible to reduce the manufacturing costs of vehicles. All the components used in the Z engine are similar to those used in common engines and compressors. For this reason, there is no need to make many changes to the component supply chain. It is possible to have a diesel passenger car without the $NO_x$ catalyst, when using the Z engine.