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HCCI-COMBUSTION IN THE Z ENGINE

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ABSTRACT

The most common car engine is a 4-cylinder 4-stroke engine. The car manufacturers have a great pressure to lower the cost of the cars and this deal also with the engines. The challenges are the coming new emission norms (for example EURO-6) and also the custom acceptance, because of the fact, that the car drives are used to the 4-cylinder engine and they want to have the same driving fun also from the new engines. A 2-cylinder 2-stroke engine has the same power output and toque as a 4-cylinder 4-stroke engine and thus it offers the same driving fun. Equal balancing is easy to make without some big additional costs, if the gas exchange of the engine is made by using poppet valves and camshafts. As there are only about 50% of the moving parts in the engine, its acceleration is even better than by a 4-cylinder engine.

One of the latest development in 2-stoke engines is the Z engine, having the compression partially transferred outside of the working cylinders. This offers new thermo dynamical possibilities to adjust the working cycle and the combustion. As there are methods to control the temperature at TDC, a HCCI-combustion is possible in the Z engine at all loads. This lowers significant the cost of the engine, as no urea injection, or NOx catalyst is needed to pass the coming EU-6 emission norm. The cost of the Z engine is lower also because of the fact that it has only 2 working cylinders instead of 4. These unique features lower the costs of the Z engine about 40%(56) compared to an equal 4-cylinder 4-stroke engine.

In 1999, Aumet Oy (51) began to research this 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, four master's theses, two SAE Papers (49,50) and four Fisita Papers have been completed on the subject. Modern simulation tools, such as Star CD, GT-Power, Diesel RK and Chemkin 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. The prototype engine made its first start in December 2004 and testing of the engine has been made two years in a test bench at VTT (Technical Research Centre of Finland).The Z engine has until now got seven international patents, several are pending and Aumet Oy has got recently the Euro patent in February 2009.

In the HCCI combustion simulation of the Z engine, a 4-dimensional ignition delay map, calculated with Chemkin and integrated in Diesel RK (52), has been used. The simulations and tests with the test engine show that the Z engine has a very good efficiency, especially at part load. A HCCI-combustion at all loads is possible in the Z engine, with lambda about 1,5-2 and EGR-rate 10-40%, depending of the load. The TDC-temperature at part load is about 800 K and at full load (bmep 30 bar) about 700 K. The HCCI-ignition, triggered with a spark plug occurs at full load between 0°- 20° ATDC and this limits the pressure and maximal temperature. NOx values are very low as the maximal temperature at full load is about 1900 K, because of the low starting temperature of the combustion, intern EGR and the expansion during the combustion. Intern EGR and active radicals stabilize the combustion (10-15).

TECHNICAL PAPER

THE Z PROCESS

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 many similarities with 2-stroke engines. The intake and exhaust valves are never open at the same time. Thus there is no loss of the fresh charge to the exhaust channel. Because the Z engine doesn't utilize the 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 external compressors. The external compression is done with a 2-stage compressor set. The first-stage compressor is a turbo charger(58). The second-stage compressor is a piston compressor that is integrated into the engine. As the pressure level in the piston compressor is only about 10% of the pressure level in the working cylinder, the compressor can be very light constructed and it is economical to produce. The temperature in the piston compressor can be kept very low compared to that of the working cylinder. This lowers the compression work. There is an adjustable intercooler after each compressor stage for the temperature control. The inter-cooling is adjusted by using bypass valves. The pressure level of the intake air after the external compression varies from 5 to 15 bar.

The combustion air is conducted into the work cylinder through the poppet valves (48,50). The intake begins when the piston is approaching the top dead centre (for example at around 60° BTDC) and the intake valves are open only about 10-15° 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 70-60° BTDC. The combustion is followed by the expansion stroke. The exhaust valves open about 60° BBDC 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 about 120° ABDC and the intake opens. Thus an intern EGR including active radicals is possible.

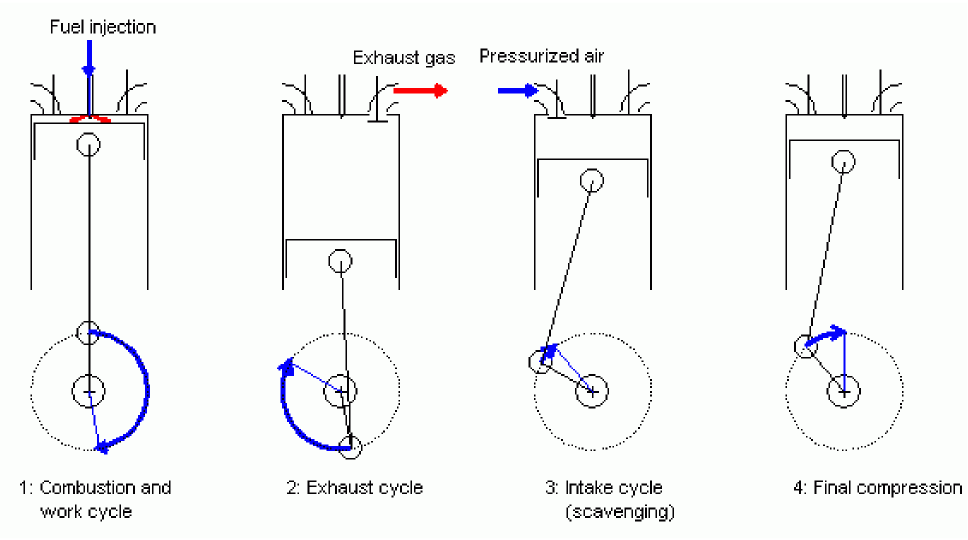

Figure 1: The process in the work cylinder in principle

The main features of the Z engine are: 4-stroke work cycle at every stroke of each piston, fully valve controlled gas exchange, diesel or Otto engine, turbo charger + supercharger (piston compressor), 2 cylinder Z engine is equal to a 4 cylinder 4-stroke engine, low emissions as HCCI combustion, low fuel consumption especially at part load, excellent transient behaviour because of the supercharger, high bmep., high downsizing degree, high mechanical efficiency as less cylinders.

The gas exchange of the Z engine has following features: gas exchange is controlled with poppet valves, exhaust valve opens about 60 ° BBDC, exhaust valve closes about 120° ABDC, intake valves open about 60° BTDC, intake valve closed about 45° BTDC, intake pressure: 5-15 bar, the velocity of the intake gas: 300-500m/s, hot intern EGR (10-40%) acts as an intern heat exchanger, hot active radicals in the intern EGR, no problems with contamination or corrosion as intern EGR, no losses of the intake gas to the exhaust channel as no overlapping of the intake and exhaust valves, pulse turbo charger: VTG, intercooler after the turbo charger, intercooler after the piston compressor with a bypass valve, variable timing of the intake and the exhaust in synchronous, electric heater in the intake channel for the cold start.

The fuel injection of the Z engine has following features: fuel injection during about 70-60° BTDC, when exhaust valves close, injection pressure: 200-700 bar, low parasite losses, injection duration 5-10°, fixed start point of the injection, high injection rate pintle type nozzle, hollow cone spray (30-46), small spray penetration, small droplets, partial fuel reforming as injection to the hot exhaust gases, rapid fuel evaporation as high temperature and low pressure during the injection (special transient area), fuel evaporation energy from intern EGR: higher heat value of the fuel, gas temperature during the start of the injection: 700-800 K, cylinder pressure during the injection: 1,5-3 bar, no swirl during the injection, no wall wetting, temperature drop of the gas in the cylinder during the injection: 200-400 K: more air into the cylinder, high turbulence after the injection as intake valves open, long mixing time before the ignition: 60-70°: homogenous mixture.

The compression of the Z engine has following features: the mechanical compression ration of the engine: 14-15:1, compression ratio in the work cylinder: IVC-TDC = 3:1-5:1, adjustable with the valve timing (secondary compression in the work cylinder), short compression time in the work cylinder; low amount of heath transfer, low compression temperature as high inter cooling rate, in intercooler condensed water aerosol cools the charge in cylinder, low compression temperature at TDC as fuel evaporation cools the gas in the cylinder before the compression, compression temperature at TDC: part load = 800 K, compression temperature at TDC: full load = 700 K, **the compression temperature lowers when the load increases**, lower compression pressure as lower gas temperature, compression temperature can be controlled with the intercooler, compression temperature can be controlled with the amount of intern EGR, compression pressure can be controlled with the pressure ratio of the piston compressor, compression pressure can be controlled with the intake timing, first pre compression in the turbo charger: pressure ratio=1,3-4, second pre compression in the piston compressor: pressure ratio=2,5-4, piston compressor well cooled: smaller compression work, high efficiency in the piston compressor as poppet valves.

The ignition in the Z engine has following features :spark assisted HCCI- ignition (SAHCCI) (1-2,8-9,16-17,20-29), ignition can be controlled with the temperature at TDC, ignition can be controlled with the pressure at TDC, ignition can be controlled with valve timing (overlap, iEGR), ignition can be controlled with **hot active radicals** in iEGR (10-15), ignition can be controlled with lambda, ignition can be controlled with the injection timing, ignition can be controlled with injection amount (iEGR, very rapid response), ignition can be trigged with a spark plug (1-2, 20-29), ignition can be assisted with a glow plug(26), late ignition: smaller heat losses, exact ignition timing possible, Chemkin used in calculations, 2% combustion of the fuel energy enough to trigger HCCI-ignition exactly.

The combustion of the Z engine has following features: HCCI-combustion at all loads as all the fuel is evaporated and mixed with the gas in the cylinder before the ignition, lambda: 1,5-2, EGR=10-40%, late combustion: smaller dp/°,late combustion: smaller p max, high bmep, as low T at TDC, low amount of EGR, rapid combustion: high efficiency and smaller heath losses, combustion duration 10-15°, low NOx and particulates as a HCCI combustion, turbulence during the combustion: good combustion efficiency, particulates and CO and HC oxidize (11), low start temperature of the combustion and EGR limit Tmax, maximum temperature 1900 K: higher Tmax than by normal HCCI: particulates and CO and HC oxidize, at part load no problems as hot EGR and active radicals (10-16) and spark ignition, no knock as the ignition occurs at the right side of the negative temperature coefficient area in the ignition delay map (7-9) Fig.5, mostly air diluted: better efficiency (2).

The expansion of the Z engine has following features: expansion during the combustion, turbulence during the expansion: particulates and CO and HC oxidize, high temperature (more than 1500 K) long time enough in order to oxidize particulates, CO and HC, the active radicals improve CO and HC oxidation (10-15), inbuilt Atkinson cycle, inbuilt variable compression ration, small heat losses as expansion at every cycle (2-stroker).

The exhaust of the Z engine has following features: exhaust from about 60° BBDC to about 120° ABDC, pulse turbo charger, pulses: 2 x 180° = 360°, low backpressure in the pulse turbo charger (54), exhaust gases hot enough for 3-way catalyst.

The valve timing affects the portion of the compression done in the work cylinder and also to the amount of intern EGR. It is useful to shift more compression to the work cylinder for example at part loads. The turbo charger in the Z-engine can use all the available exhaust gas energy at all load conditions and thus no waist gate is needed. This improves the efficiency of the engine. The Z engine can also utilize the Otto cycle. The knock phenomenon, found at high geometrical compression ratios and pressures, can be avoided, because the compression temperature can be controlled separately (1-2, 8-9). A higher overall efficiency could be gained because of the high compression ratio and better controllability especially at part loads. The Z-engine utilizes Atkinson cycle and it has an inbuilt variable compression ration.

THE INTAKE FLOW

The theoretical flow behaviour in the intake valves can be seen in Fig. 2. The intake valves have a special shape to form Laval nozzles (53). The pressure difference, intake channel /cylinder is received from a simulation of the engine. The required ratio between the exit area of the valves and the throat area(calculated as Laval nozzle) has been calculated. The calculated exit area/throat area ratio has been taken from the valve lift data and the valve dimensions (50).

In the calculations the intern exhaust gas re circulation (iEGR) rate in the cylinder was 20% and the exhaust gas was not assumed to rotate at the beginning of the intake. The flow coefficient of the intake valves is high, about 0,9, because the flow is a nozzle flow. The temperature of the intake air lowers about 30-50 K because of the very high intake velocity. The turbulence energy in the cylinder after IVC is about 60 J/g gas. Fig. 2 shows the situation at about 45° BTDC, when the injected fuel has already evaporated.

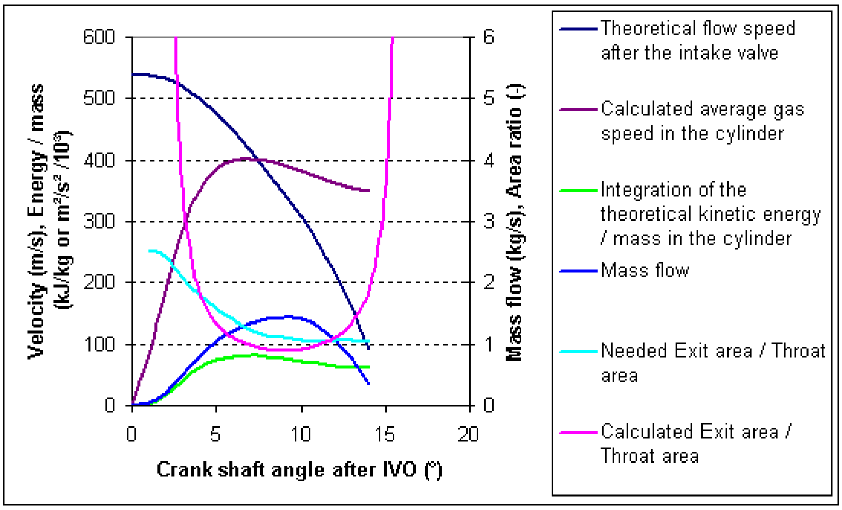

Figure 2: The theoretical valve flow

THE FUEL INJECTION

The fuel pintle nozzle injector forms a hollow cone shape spray (30-46). These types of injectors have a 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 200-700 bar, increases the efficiency of the engine by 1-2% compared to engines using 1600-2000 bar. This type of a low pressure injector is ideal at back pressures up to 3 bar, (30). The injection occurs at this pressure in the Z-engine, between 70-60 deg BTDC. The thin fuel film, thickness of 0,05 mm and the high flow area, about 0,5 sqr. mm, make a good atomisation and a short injection period possible (30-46).

THE Z-HCCI COMBUSTION

In order to reduce NOx, it was developed a swirl less late HCCI combustion. The fuel injection of the Z- HCCI combustion occurs at about 70 - 60° BTDC, when the temperature in the cylinder is about 700-800K (depending of the load) and the exhaust valves are closing and the pressure in the cylinder is about 1,5-3 bar. This special transient area of the gas exchange of the Z engine makes a very rapid evaporation of the droplets possible. (The pressure in the cylinder of a conventional diesel engine is in this situation about 10 bar).

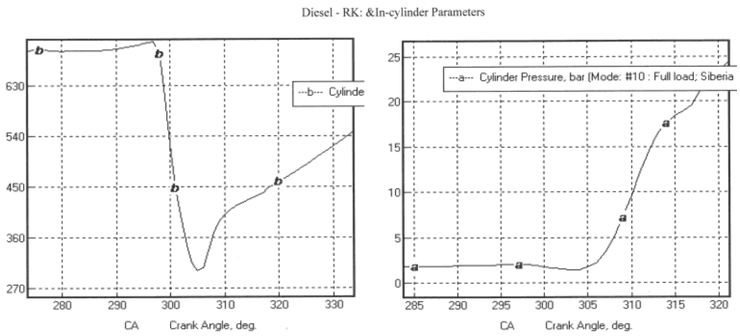

Figure 3: The temperature(K)- and pressure(bar) curves between 80°-40° BTDC

After the fuel injection the intake valves open and the high velocity gas flow creates a high turbulence in the cylinder. This makes a rapid mixing and HCCI combustion possible, as well as the long mixing time, 60-70°, before the ignition. The special spark plug ignition activates the cool flame and it acts as an amplifier to ignite the HCCI mixture at about 0-20 ° ATDC.

The low pressure fuel injection makes a late HCCI-combustion possible as the compression temperature at TDC do not exceed 700-800 K depending on the load and thus the cool flame don't appear automatically and the mixture don't self ignite. By this way it is possible to trigger the ignition of the HCCI-mixture at 0-20° ATDC. From this point the down wards moving piston lowers the pressure- and temperature rise during the combustion.

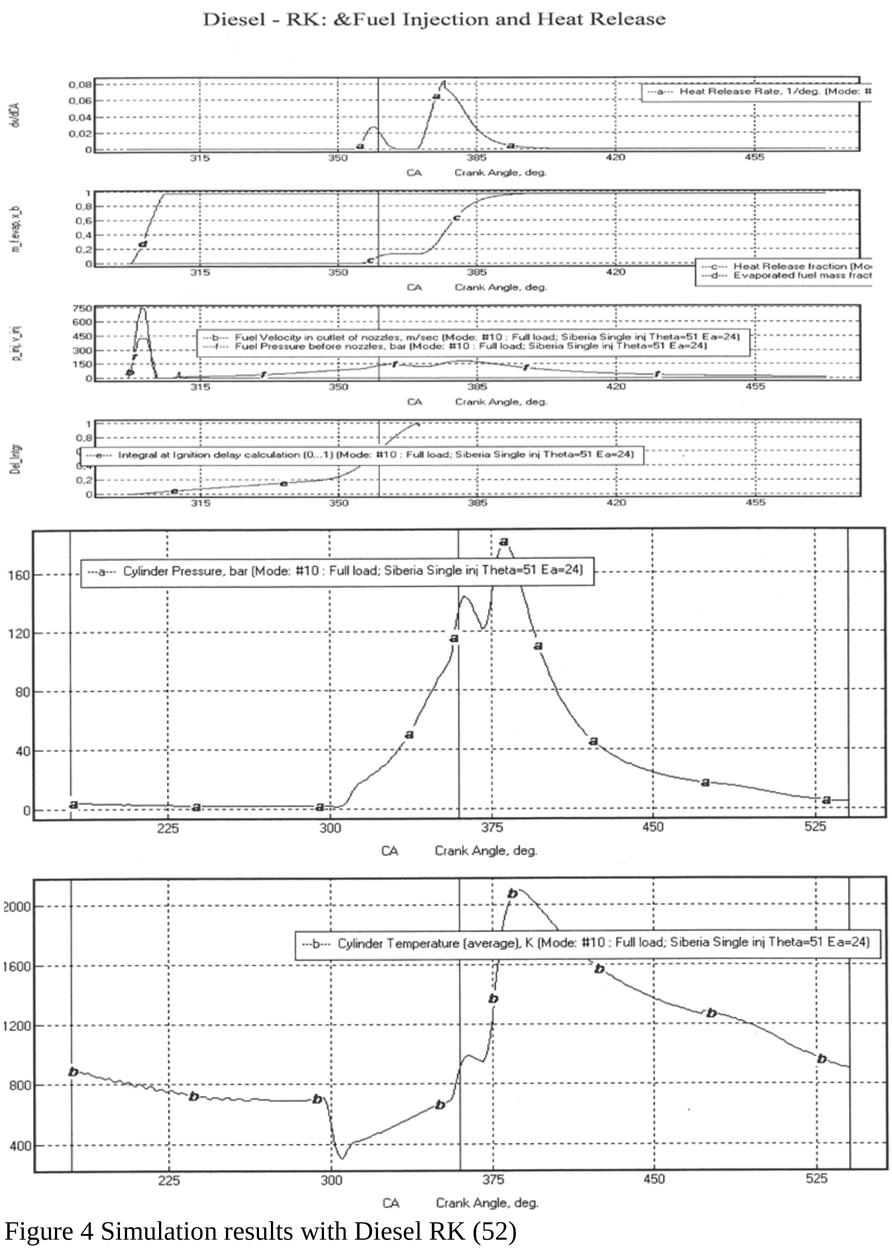

Figure 4 Simulation results with Diesel RK (52)

The pressure rise in Z-HCCI combustion is at bmep 29, about 7,5 bar/deg, lambda = 1,2 and EGR = 15%. Note the "twin peak" in the pressure curve. The 4-dimensional ignition delay map, integrated in Diesel RK, has been calculated with Chemkin (5 page5, 52, 55 page 14)

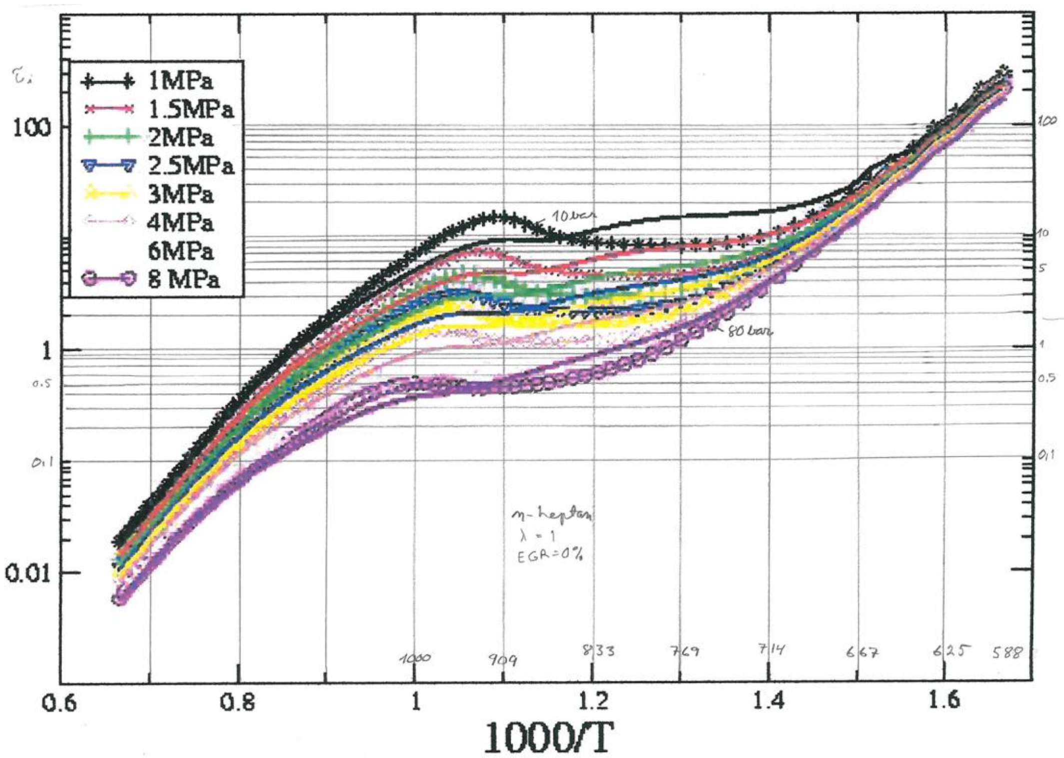

Figure 5: The ignition delay curve (ms) of HCCI mixture.

In order to understand this phenomenon and how to define the exact ignition in the Z engine, it is useful to study the ignition delay map of n-pentane, where the variables are temperature and pressure. We can follow the path of the mixture, when the piston moves from (for example) -40 deg to TDC. If the rotation speed is about 1700 rpm, so 10 deg=1 ms. The pressure- and corresponding temperature values can be taken from Fig.4, starting from 320°. As lambda in the Z engine is for example 1,2, this is equal to about 2500 J/g air. At TDC conditions, for example: p=100 bar, T = 700K, the needed energy to rise the temperature of the mixture for example 50K to ensure the exact ignition point, is about 50 J, or 2% of the energy of the mixture. According to the map, Fig.5, this change shortens the ignition delay from 3 ms to 0,9 ms. This very high sensitivity of the ignition point makes it possible to define the main ignition very exact by igniting first about 2 % of the fuel. This ignition activates the cool flame and thus it is possible to use the cool flame as an amplifier in order to trigger the main ignition at about 0-20° ATDC, depending on the load. The down wards moving piston limits the pressure rise and makes this unique combustion system possible. This type a hybrid combustion is called spark-assisted HCCI, SAHCCI (1-2).

As the Z-HCCI combustion is rapid, the weight point of the combustion is not far from TDC and thus the efficiency of the engine stays high. This also lowers the heat losses close to TDC during the Z-HCCI-combustion. The amount of the intern EGR is easy to adjust, for example by throttling the exhaust channel.

.The Z-ignition occurs always at the right side of the negative temperature coefficient (NTC) area and the negative temperature effect decouples ignition front and acoustic wave coupling and no ignition to detonation transition (knock) occurs in the Z-HCCI combustion (7-9). See also the ignition delay integral in Fig. 4, value 0-1: ignition when it reach value 1.The uniformity of the mixture affects to the ignition and combustion, as can see, when comparing with experimental data.

The combustion duration and the amount of the cool flame, depending on temperature, pressure, EGR, lambda and rotation speed(55, 57) has taking in account in the simulations The combustion can be described by using three Wiebe functions, one for the cool flame, one for the main combustion and one for the “tail”. We are working with this problem, but when comparing with the experimental data and calibrating the model in the calculated load points, a good accuracy can be reached. The more sophisticated way to calculate the combustion shall come later in the simulations.

In order to limit maximal temperature to 1900K, lambda was in the simulations 1,8-2, depending on the amount of EGR and load. The dilution with air mostly increases the efficiency. As Z engine is a two stroke HCCI diesel engine with spark ignition, active radicals “survive” easily, as from IVO to TDC is only about 60°, when in port scavenged two stroke engines this is about 220°. This makes the spark ignition possible without problems, as the active radicals lower the activation energy, needed in the ignition ,to one tenth .This is not the case in four stroke HCCI engines(10-15).

Z-ENGINE, AN ECONOMICAL ALTERNATIVE TO A HYBRID SYSTEM

Having the cylinder bore 72 mm and stroke 70 mm, the Z engine has 38% part load efficiency and 41% best point efficiency. As the combustion is homogenous at all loads, NOx and particulate emissions are almost zero and no NOx or particulate filters are needed. This reduces the costs of the engine about 800-1000 euro. An additional cost reduction comes from the low pressure injection system and reduced number of cylinders, smaller weight and size (47, 56).

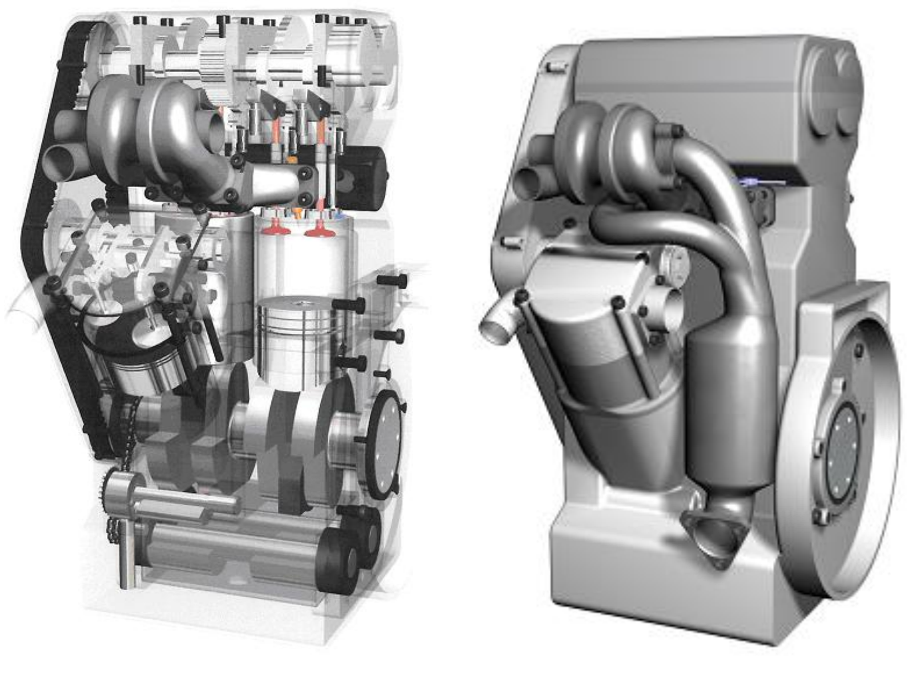

Figure 6: The Z engine, 2-cyl, 0,58 l, 80 kW 3500 rpm, bmep 30 bar

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