AN INNOVATIVE EXHAUST GAS AFTER TREATMENT FOR A TWO STROKE MICROCOGENERATION UNIT

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Abstract
A compact and low cost spark ignition two stroke engine could be suitable for many applications, especially for car range extenders and microcogeneration units. An innovative opposed piston two stroke engine has been designed and developed at CNR Istituto Motori for microcogenerative applications, showing very interesting characteristics in terms of high efficiency and low noise and vibrations. On the other hand, higher emissions have been recorded, needing for an innovative after-treatment system in order to respect the new stringent regulation. In this Paper an unconventional system has been proposed, consisting in a oxidative reactor placed before the oxygen sensor and a three way catalyst (TWC). This pre-treatment notably enhanced the stability of control system and the efficiency of the TWC, so resolving a significant issue of high speed two stroke engines.

Emission issues for two stroke engines

Two stroke engines are considered a very interesting power and propulsion systems, powerful, lightweight, simply constructed and suitable for a lot of applications; on the other hand, they have been almost completely abandoned during the last years because of their low efficiency and very high gaseous emissions. Many attempts have been made in order to solve these problems, like direct injection systems, different scavenge schemes and high efficiency after-treatment systems. The reasons for which it is not possible for them to obtain lower emissions are strictly related to the poor scavenge efficiency, i.e. the fluid dynamic process which replaces exhaust gas with a fresh charge. For this reason, a significant amount of burnt gas remains inside the cylinder (causing a bad combustion, quenching and misfiring) and a similar amount of fresh charge is pushed out at the escape (the so called “short circuiting”), causing high specific consumption and very high emissions [1].

To solve the short circuiting issue, direct injection systems have been introduced, as the scavenge process is done only with air and the delivery of fuel is operated when the cylinder has no communication with the external environment. On the other side, this solution also involves a bad interaction of fuel with the trapped fluid inside of the cylinder (which results a mix of fresh air and burned gas), as a very short time is available to allow the complete vaporization of fuel droplets, because of the relatively high revolution speed. Also, the distribution of exhaust gas inside the air is not uniform in the cylinder volume, making the formation of a stoichiometric fresh charge even more

critical, with a strong variability of the air/fuel ratio in the chamber and, consequently, a bad combustion and high emissions. In fact, a significant amount of unburned fresh charge (much higher than in four stroke engines) is produced, leading to high HC values together with the presence of CO and O_2, each of them confirming an incomplete combustion process.
In order to improve scavenge operation, many different schemes have been proposed, such as uniflow scavenge by means of opposed piston or poppet valve. Unfortunately, these solutions are more complicated and bulky and they don't solve completely the short-circuit issue, which can still be the cause of unacceptable emission levels.
As regards after-treatment systems, a lot of schemes have been proposed, most of them just considering the oxidation step, as NOx emissions could not be treated in any case, because of the air deriving from short-circuiting and misfiring. This aspect was not considered as an issue in the past, because NOx emissions were considered quite low (if compared to four stroke engines) due to the considerable presence of burned gas which, coming from the previous cycle, reduces the temperature peak during combustion, so acting as an internal EGR (Exhaust Gas Recirculation). Nevertheless, the present regulation cannot accept these NOx emissions, which result far away from the last stringent limits; so that the adoption of a high efficiency stoichiometric three-way process in the after-treatment apparatus is essential. As well known, even in case of stoichiometric feeding conditions (at the intake), an engine normally produces HC, CO and NOx at the same time, but not in a fixed proportion, this because of the ever changing combustion conditions (typical of alternative engines) which constantly deliver exhaust gas to TWC with a different composition. For this reason, in order to make the engine work in the best way, a closed loop electronic control modifies the injection parameters (opening time) based on the feedback coming from oxygen sensor at the escape, so to get a dynamic equilibrium around stoichiometry. The capability of converting all the different species depends on the aptitude of accumulating oxygen during NOx reduction (the so called "oxygen storage"), in order to allow the HC and CO oxidation also during rich air/fuel feeding. Obviously, with a higher combustion instability (due to misfire and quenching) and/or short circuiting, a higher fluctuation in respect of stoichiometry takes place, together with a lower efficiency of TWC and minor control system stability. In a two stroke engine these aspects are even more critical for the following reasons:

1) The massive presence of air in the exhausts due to the scavenge process (both in case of manifold injection and direct injection) can mislead the feeding control system. In fact, also adopting an air metering system at the induction, the oxygen sensor will detect a lean combustion even in case of stoichiometric or rich running conditions. This can easily cause instability for the control system and a much higher production of polluting substances.
2) Circumstances for misfiring or partial combustion are very common for two stroke engines especially if provided with crankcase pump, because of low purity of fresh charge and due to poor efficiency of scavenge, with consequent

high levels of O_2, HC and CO. These species cannot be completely treated by a catalyst because of the structure and overall dimension of the reactor itself, which does not permit an adequate residence time for gas.

3) The contemporary presence of high levels of O_2, HC and CO on a TWC catalyst is unsuitable for the complete NO_x reduction into N_2, because the above mentioned substances, when existing in significant amounts at temperatures below 400°C, start competitive phenomena with NO_x, inducing a low efficiency in conversion rate and a potential production of NH_3 [2]. On the contrary, when gas temperature is above 400°C and in presence of an atmosphere rich in water vapor, the CO conversion into CO_2 does not affect the NO_x reduction as described below. However, when the conversion is not complete, it can cause the production of a significant amount of H_2 (through water gas shift reaction, WGS, or steam reforming reaction, SR), which, combined with NO, is the main responsible for the NH_3 formation [3]. To drastically reduce the NH_3 production, a higher working temperature (higher than 530°C) on the catalyst is favorable [3], while a complete elimination (lower than 10 ppm) could be possible only with an ASC catalyst [4].
4) The low NOx production is an issue for the complete HC and CO oxidation (which is much higher) as an inadequate amount of oxygen could be available after the reductive process.

For the above mentioned reasons, even adopting all these solutions as a whole (direct injection, improved scavenge and TWC) two stroke engines could never meet the new stringent regulation regarding emissions, both in automotive application and in power generation (cogeneration). In fact, the best percentage cut of emissions can hardly reach a value of 80%, while modern four stroke engines can attain a 95% almost in all operating conditions. Also, two stroke engines are normally lubricated with oil injected at the air intake, whose presence represents a very important issue for the TWC as the lubricant directly takes part to the combustion process. In fact, the oil which result unburned (or partially oxidized) can easily jam the catalyst and dramatically reduces its global efficiency as it covers the reactive surface. In any case, even in case of modern engines (with reduced oil need) the system cannot completely oxidize lubricant traces in the exhaust gas, this being the cause of smoke and heavy dangerous hydrocarbon emissions.

An innovative after-treatment system for two stroke engines

Some recent experiences at CNR Istituto Motori on an innovative opposed piston two stroke engine (which is part of a 3 kWe microcogeneration system) and provided with a manifold fuel injection system together with a TWC at the escape, have showed a noteworthy performance in respect of control stability depending on oxygen sensor position. In the following Fig. 1 is reported the experimental engine and the after-treatment system (contained in the black case on the right of Fig.1), which also contains the heat recovery system and the muffler.

Fig. 1 Experimental opposed piston two stroke engine

In fact, when the oxygen sensor was placed before the catalyst, the system could not manage the injection in order to get a rigorous stoichiometry, as the air presence, derived from short circuiting and misfiring, misled the whole control, with deep instability and very high emissions (before and after the catalyst) as reported in the following Tab 1.

	HC [ppm]	CO[%]	NOx[ppm]	O_2 [%]	Temp.[C]	Osc. time [s]
Untreated	3930	2,2	680	1,9	555	1,9
After TWC	1760	1,3	460	1,1	580	1,9

Tab 1 Global emission with oxygen storage before catalyst

On the contrary, placing the same oxygen sensor after the catalyst, a quite different behavior has been recorded; the global performance in terms of emission (always before and after the catalyst) is reported in the following Tab.2

	HC[ppm]	CO [%]	NOx [ppm]	O_2 [%]	Temp. [C]	Osc.time [s]
Untreated	2160	1,7	740	1,4	525	0,4
After TWC	1220	0,8	510	0,8	560	0,4

Tab. 2 Global emission with oxygen sensor after catalyst

As it can be easily seen, in this way the catalyst completed the HC and CO reaction with the oxygen which could not take place inside of the engine, eliminating most of these gases and filtering their fluctuations over oxygen sensor. In fact, this massive presence could not correctly consent the fundamental mission of the control system and, therefore, the fixing of the effective stoichiometric air/fuel mixture. On the other hand, the consequent lower variability in the composition of the exhaust mixture dramatically enhanced the efficiency of the same reactor, because the time duration and amplitude of the rich/lean fluctuations resulted much shorter (about 0,4 s instead of 1,8 s on average) and more compatible with the effective oxygen storage capability of the reactor. Nevertheless, the produced emissions resulted still quite high and far away from current regulation for small cogeneration units, and this probably because of TWC which was not able to attain a significant efficiency, even if working at a quite high temperature. After some analysis of the above seen performances it was clear that exhaust gas composition was quite far from an ideal condition, as it was characterized by the following features:

1) Oxygen presence.
2) Very high presence of HC, CO and low NOx, which does not represent the best conditions for NOx reduction and oxidation of HC and CO.
3) Existence of unburned lubricants.

All these aspects together (control issue and TWC efficiency) suggested that an oxidative pre-treatment system of the exhaust gas (by means of a specific reactor placed before both oxygen sensor and TWC) would be very interesting in order to get the elimination of every fluctuation of the exhaust gas composition over both oxygen sensor and TWC through the following parallel actions:

1) Combustion of HC and CO deriving from short-circuiting, quenching and misfiring (flow always provided with oxygen);
2) Filtering the fluctuation of HC, CO and NOx deriving from real combustion and fuel feeding system (flow alternatively provided with oxygen) and balancing the relative amounts.

Regarding the last aspect, this stage should have a very high active surface and a large number of cavities which could physically trap (through viscosity) a significant percentage of the gases passing in that moment in the reactor. In this way the system should alternatively hold back gases with different characteristics deriving from regulation around stoichiometric conditions. So, exhaust gas deriving from rich feeding (full of CO and HC) could react with gas coming from lean feeding (full of O_2) in order to complete the oxidation and reduce the amplitude of these fluctuations. Regarding the specific application to a two stroke engine, the oxidative pre-catalyst (OPC) when fed with exhaust gas deriving from a lean mixture could reduce the higher amounts of HC and CO in order to balance their presence in respect of the lower produced NOx and at the same time to burn the captured oil droplets, which could react with oxygen with a higher residence time. After having compared many different reactors typologies, an automotive particulate trap, characterized by a cordierite structure with a diameter of 90 mm, 200 cpsi (cells per square inches) and coated with Pt (25g/cu^3), has been chosen as OPC. Moreover, a TWC catalyst (with Pt, Rh), characterized by a 400 cpsi and coated with Pt (at 20g/cu^3) and Rh (at 4 g/cu^3) has been selected among other commercial models. In the following Fig. 2 the above described elements are shown; the oxygen sensor is placed between the two elements, before TWC.

Fig. 2 OPC (left) and TWC (right)

The obtained system showed a very interesting behavior in terms of stability of regulation, with a shorter fluctuation around stoichiometry (about 0,27 s on average) if compared to the previous case without OPC and oxygen sensor placed after TWC. In the following Tab.3 are reported the emissions before and after OPC and after TWC.

	HC[ppm]	CO [%]	NOx[ppm]	O_2[%]	Temp. [C]	Osc.time [s]
Untreated	2050	1,6	650	1,4	520	0,35
After OPC	45	<0,01	670	<0,01	610	0,35
After TWC	15	<0,01	60	<0,01	620	0,35

Tab.3 Global emission with oxygen sensor after OPC and TWC

Conclusions

As it can easily seen, rough emissions are even better than in the previous case (due to a lower instability of control system) and, after OPC, the HC and CO emissions resulted absolutely reduced and much lower than the values obtained with a TWC only, together with a quite complete absence of oxygen. Also, after TWC the global emissions result notably reduced, with the TWC shoving a very high efficiency (higher than 90%) not only on HC and CO but remarkably on NOx.

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