Reduction of cold start emissions with microwave heated catalytic converters

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1 Introduction

Emissions of Euro-6 gasoline powertrains at normal operating temperatures are almost zero (Fig. 1). On the contrary, during cold starts, characterized by low temperatures for the catalytic converters, CO and unburned hydrocarbon (HC) emissions are 2-3 orders of magnitude higher than during cruise operating conditions [1]. The situation is even more severe with hybrid powertrains. Here the intermittent engine operation often leads to numerous cold starts. In parallel, the steadily increasing efficiency of modern engines has dramatically lowered exhaust gas temperatures, both in gasoline and diesel engines (first law of thermodynamics). All near-future engine concepts will face increasing difficulties conflicting with the fuel saving imperative in providing the necessary heat for the pollutant aftertreatment. Depending on the application, load conditions and aftertreatment technology, sometimes "artificial" supply of energy to the catalytic converter is required in order to meet emission limits. One potential solution was the utilization of electrically heated catalytic converters. Electrical Heated Catalysts (EHC) that uses mechanical energy from the engine to generate the electrical energy to heat up the exhaust gas upstream the catalytic converter is proposed in [2, 3, 4, 5].

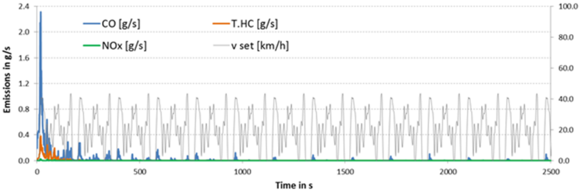

Figure (1) – Passenger car (Euro- 6) emissions with a gasoline powertrain during the IUFC-15 cycle (measurements at Empa APTL).

In literature, microwave heating is often applied to chemical reactions: [6] discusses different designs for microwave field applied to Small-Scale Chemical Processing. In the exhaust aftertreatment field, microwaves have been used for initiating active regeneration of particle filters [7], as well as for sensing the urea level in an SCR catalytic converter [8, 9].

In this study, we describe a microwave heating system applied to catalytic converters for automotive applications and we show its relevant contribution in emissions reduction during cold start conditions. Experiments with synthetic exhaust gas and inflow gas temperature of 20°C have shown conversions of more than 60%. A vehicle size system mounted at the end of the tailpipe of a gasoline vehicle achieved a reduction of

15% of cumulative emissions in the first 600s after cold start. Further optimizations related to higher microwave power, substitution of conventional honeycomb (HC) with additive manufactured polyhedral catalytic converters and to improved layout have the potential to further increase cold start emission conversions.

2 System design

Heating the catalytic converter with microwaves requires a microwave source, a wave guide, which is an extra volume responsible for the wave transmission from the source towards the cavity, and the cavity, where the catalytic converter is placed and the stationary microwaves develop. Each of these components has to be dimensioned and tested. A household (kitchen appliance) magnetron was chosen as a microwave source. The power of 1.3kW was deemed as sufficient. The low price of such mass produced components was an additional argument for the choice. Moreover, the materials of the entire catalytic converter, or at least parts of it, have to be good microwave absorbents.

2.1 Material selection

Conventional cordierite ($MgO-SiO_2-Al_2O_3$) is not absorbing microwaves. SiC proves to be the material of choice. SiC is already widely used in exhaust aftertreatment based on its good thermal and mechanical properties. In order to achieve the best dielectric properties, different slurries of SiC have been prepared and analyzed. The catalytic converter used in the present study comprises of a sequence of slices, each of identical cylindrical shape, either out of SiC or Al_2O_3. SiC slices have been taken out of a non-coated DPF, 200cpsi, and have been coated in house with Al_2O_3/Pt (60-70grPt/ft3). Coated SiC slices are denoted by SiCc. For testing only the microwave absorption, sometimes, non-coated SiC slice have been used. In these cases they are denoted by SiC. The Al_2O_3 slices have been reused from another project. They had a foam structure and have been coated with Al_2O_3/Pt by an industrial coater. The notion used therefore is Al_2O_3c. Thus, the catalytic converters used in this study have rather an oxidative and reduction behavior.

2.2 Cavity design

A sophisticated system composed by the microwave guide and the cavity for vehicle size applications has been designed based on simulations. Proper system dimensions must be chosen in order to obtain stationary waves in the cavity. The dimensions of the waveguide are mainly given by the wave length (=v/frequency) of the microwave. The cavity diameter was chosen in order to have typical passenger car catalytic converter dimensions. The length was a result of the simulations in order to enable the best stationary wave (Fig. 2). The microwave cavity is made out of steel or aluminum with bolted connections. The designs avoided any welded metal connections since the interaction of austenitic steel with microwaves is not so clear. The presence of the catalytic converters was neglected in the simulations in order to obtain an optimal design in an acceptable computational effort. For further optimization and development the detailed modelling of the interaction of the catalyst with the microwave is indispensable. Based on the simulations results, the system described in Fig. 2 has been realized (Fig. 3). Unfortunately, there is no way to position a thermocouple in the cavity. Thermocouples are immediately destroyed when the microwave is on.

All measurements have been accompanied by microwave sensors in order to identify possible escape of the microwaves form the cavity. No leaks have been ever identified. Thus, no further actions have been considered as necessary in this field.

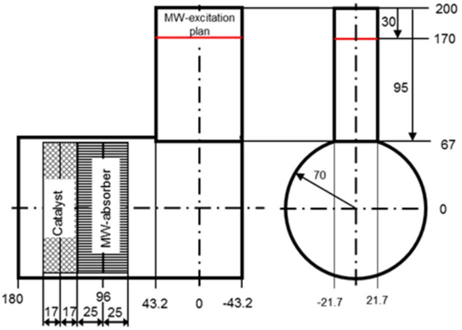

Figure (2) – Technical dimensions of the microwave guide and of the cavity.

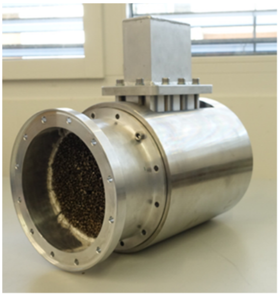

Figure (3) – Microwave guide and cavity apparatus.

3 Experiments

3.1 Preliminary experiments with synthetic exhaust gas

A synthetic exhaust gas of 295 liter/minute comprising of 800ppm CO mixed with air at 20°C as inlet temperature was tested with the apparatus described in section 2. Several concepts in terms of number, sequence and position of different slices out of SiC and Al_2O_3c have been tested in order to define the optimal one. It is worth noting that in all the experiments the synthetic exhaust gas had no water vapor. Microwave heating started at 50s and it was kept switched on for 200s.

Fig. 4 reports the different configurations that have been tested:

A. 1 SiC slice (uncoated acting as microwave absorbent) and 1 Al_2O_3c slice (oxidative catalytic coating as described in section 2.1),

B. 2 SiC and 2 Al_2O_3c slices,

C. 1 SiC and 2 Al_2O_3c slices,

D. 1 SiC and 2 Al_2O_3c slices, in an optimized position with respect to c), based on the simulation results.

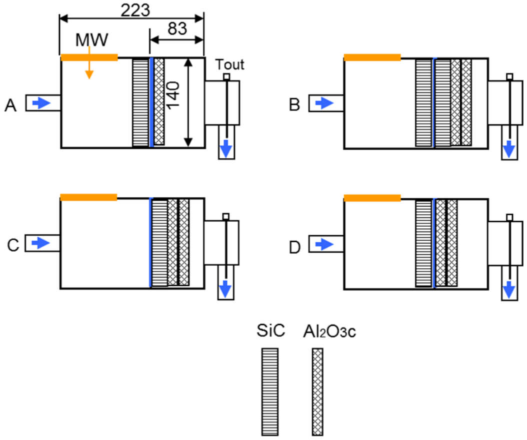

Figure (4) – Schematic of the tested concepts in the designed cavity, in orange the wave guide.

Fig. 5 represents the outlet temperature profile in time with the different configurations described in Fig. 4. It is evident that:

- The flow enters at 20°C. The microwave heating system is increasing the flow temperature immediately.
- The microwave heating increases the temperature at discrete spots in the catalytic converters, where the reactions start happening. The larger part of the gas passes through the unheated parts and remains at 20°C. Thus, the temperature measured in the catalytic converter exit corresponds to the mix of cold and heated gases.
- The highest temperature is reached with case A, corresponding to the configuration with lower thermal inertia (lower mass). As long as cases C and D, characterized by lower thermal inertia with respect to case B, have lower temperature with respect to case B, this means that, in case B, more reactions are happening.
- Among cases C and D, case D confirmed the optimization.
- Due to the higher inertial mass, case B reaches maximum temperature later in time with respect to the other cases.

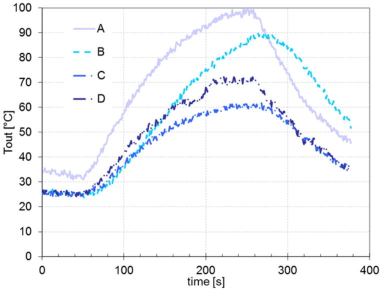

Figure (5) – Catalytic converter Outlet Temperature with a synthetic gas flow of 295l/min and 20°C at inlet.

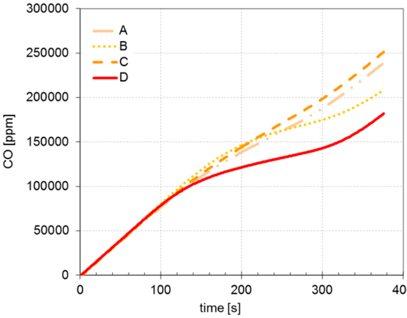

Figure (6) – Cumulative CO profile in ppm with a synthetic gas flow of 295l/min and 20°C at inlet.

In Fig. 6 the corresponding cumulative outlet CO emissions are reported. Main conclusions are:

- The optimized configuration, case D, resulted in the highest emission reduction. Instantaneous CO oxidation reached 75%, while cumulative CO oxidation 42%, this at gas inflow temperature of 20°C.
- The higher conversion reached by case D in respect to case C is clearly due to the optimized positioning of the SiC slice; a better positioning in respect to the location of the next maxima of the stationary (micro-)wave.
- Case B with 2 SiC and 2 Al_2O_3 slices reaches higher conversion in respect to cases A and C although it has higher thermal inertia. The additional SiC slice in case B absorbs more energy from the microwaves.
- Case A reaches the highest temperature (Fig. 5) but is characterized by the lowest conversion (Fig. 6). This evidences that additional catalyst slices and additional microwave absorption capacity have the potential to further improve the system's behavior.

3.2 Extended measurements with synthetic exhaust gas

Based on the first results, a vehicle size catalytic converter with a volume of approx. 2lt has been configured. Measurements with synthetic exhaust gas (with more complex composition) and at higher gas flows aimed to identify a configuration suitable for vehicle applications. The behavior in the preliminary measurements suggested testing of catalytically coated SiC slices, thus slices absorbing microwaves as well as acting as reactors, should the local temperature exceeds certain levels.

The synthetic gas flow was set at 600 lt/min, comprising of 1000ppm CO, 1000ppm C_3H_6, 5%O_2 and N_2 for balance at 20°C as inlet temperature. It is worth noting that in all the experiments the synthetic exhaust gas had no water vapor. Similar to the measurements presented in the former section, the gas flow enters the cavity with ambient temperature (20°C).

New configurations with additional slices have been compared in terms of HC and CO oxidation (Fig. 8). In all the configurations except for case e, the microwaves are switched on after 50s from the beginning of the flow. In case e a slightly different strategy was followed. The microwave was switched on 75s before the entrance of the gas flow in the catalytic converter, thus case e is characterized by 50s of preheating of the catalytic converter. In all configurations the microwave heating was operating for 150s. Fig. 7 shows a schematic of the tested assemblies:

a. Configuration number 1, with 1 SiC uncoated slice, 2 SiC coated slices and 1 Al_2O_3c slice and x=30mm,

b. Configuration number 1, with 1 SiC uncoated slice, 2 SiC coated slices and 1 Al_2O_3c slice and x=50mm,

c. Configuration number 2, with 1 SiC uncoated slice, 2 SiC coated slices and 2 Al_2O_3c slices and x=55mm,

d. Configuration number 2, with 1 SiC uncoated slice, 2 SiC coated slices and 2 Al_2O_3c slices and x=50mm,

e. Configuration number 2, with 1 SiC uncoated slice, 2 SiC coated slices and 2 Al_2O_3c slices and x=55mm. Thus identical to case c, but 75s of the 200s of preheating of the catalytic substrates is without flow through.

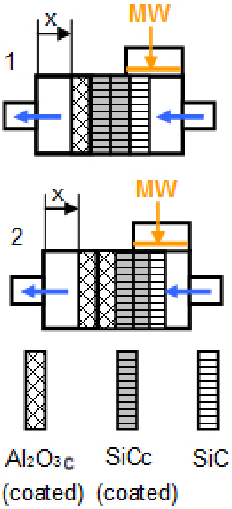

Figure (7) – Tested configurations for identifying the optimal catalyst for vehicle testing.

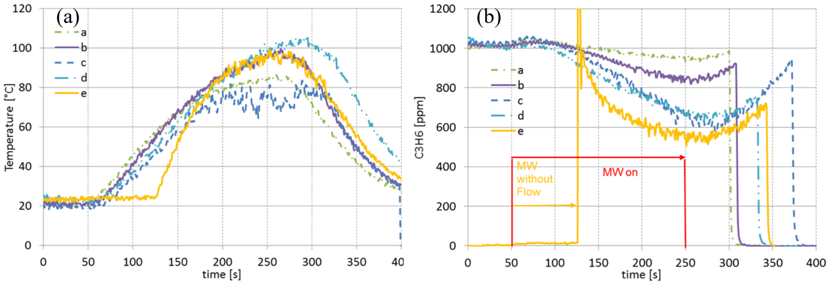

Figure (8) – Temperature profile (a) and C_3H_6 emissions in ppm (b) with a synthetic gas flow of 600l/min and 20°C at the cavity entrance.

Fig. 8 presents the outlet temperature profile and the C_3H_6 outlet concentration respectively, over time, obtained with the different configurations. Without switching on the microwaves, no reactions and no conversion have been detected as well as no temperature increase over the cavity.

Case e with the 75s of preheating of the slices with the microwaves resulted in the highest conversion and among the highest gas temperature increase over the cavity. C_3H_6 oxidation exceeds 50% and this at gas inlet temperature of 20°C. All cases (c,d,e) with the higher number of slices resulted in higher conversion. The preheating, not only increases conversion, but also contributes in reaching it earlier. The results confirm that the temperature and emissions are sensitive to the position of the catalytic converters.

3.3 Vehicle Experiments

A system similar to the configuration 2 in Fig. 7 has been mounted at the end of the tailpipe of a gasoline vehicle. (Fig. 9). It is impossible to mount the microwave heated catalyst system in the conventional position of the serial catalytic converter without the collaboration of an OEM and access to the ECU. The position for microwave system is the most unfavorable, since, during cold start, the exhaust has to flow through and warm up the original vehicle catalytic converter (near the exhaust manifold) and the entire exhaust gas guiding system (pipes and mufflers), thus arriving with the lowest temperatures at the additional, microwave heated catalyst system. The exhaust gas temperatures at the tailpipe, and thus upstream the microwave heating system, remain below 100°C even 600s after engine start.

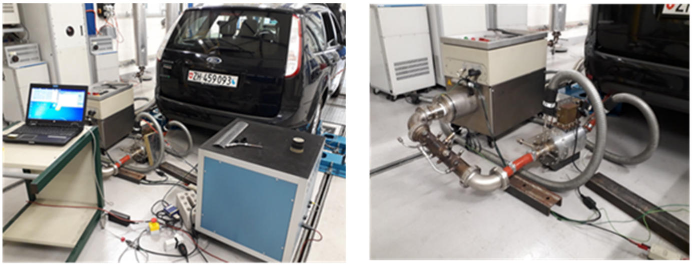

Figure (9) – Installment of the new catalytic converter at the end of a vehicle tailpipe on the chassi dynamometer.

The vehicle was tested on the chassis dynamometer where the first 15 minutes of a WLTC cycle have been followed. A series of cold starts (20°C) has been performed. After each cold start, no vehicle activity followed for 4 hours in order to allow all relevant parts of the vehicle to cool down to the ambient temperature of 20°C. The electrical power consumed by the magnetron for generating the microwaves has been kept at 1.3kW, a pre-heating time of 100s was selected while the microwave was switched on for 300s in total. The emissions before and after this "tailpipe" catalytic converter have been analyzed. Fig. 9 shows the vehicle installment as well as the catalytic converter positioning and the emissions analysis setup.

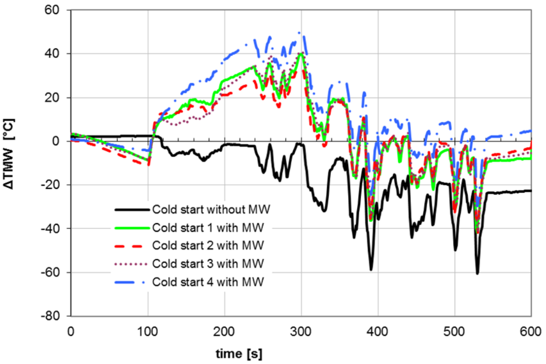

Figure (10) – Temperature difference over the catalytic converter during 5 cold starts (4 with microwave and one without microwave preheating).

Fig. 10 shows the temperature difference over the catalytic converter during 5 different cold starts. The temperature difference over the catalytic converter is negative without the microwave heating (solid dark line). The exhaust gas loses heat in order to heat up the cold converter. In contrast, the temperature difference over the catalytic converter is positive in all cases as long as the microwave heating is switched on. The differences among those cycles are attributed to the differing catalyst activity. This in turn, can be attributed to the variation of the unburned hydrocarbon amounts coming from the engine in the different cold starts.

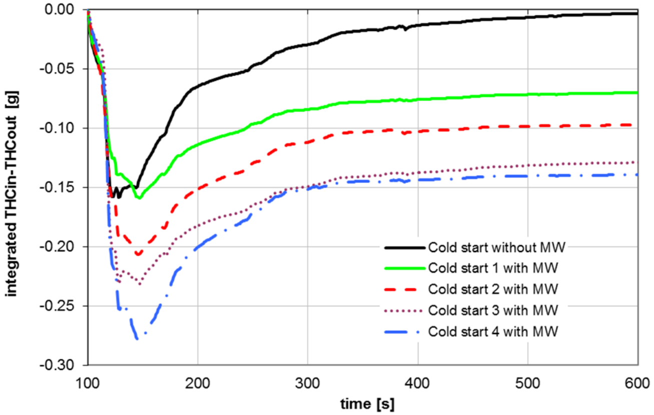

Figure (11) – Cumulative Total Hydrocarbon emission during a series of cold starts.

In Fig. 11, the solid dark line represents one measurement with no microwave heating. Microwave heating system allows a cumulative emission reduction in the initial 600s after cold start of around 10-15%. Based on these measurements and observations it is expected that a similar system will reduce cold start emissions for more than 30% if positioned near the exhaust manifold, a position typical for state of the art aftertreatment systems.

4 Conclusions

A System for heating up the catalytic converter during cold starts has been developed and tested. Based on a conventional 1300W magnetron, the system comprises of a waveguide, a cavity and microwave absorbing components. As microwave absorbents, SiC honeycomb substrates have been used. Such substrates, catalytically coated, showed the highest pollutant conversion performance at low temperatures.

In synthetic gas supplied at 20°C, pollutant conversions have exceeded 50% with the optimized configuration. At the tailpipe of a vehicle a similar system has achieved a reduction of 15% of the emissions in the first 600s of the WLTC cycle.

The system's performance will increase if mounted in position nearer to exhaust manifold and by using a stronger magnetron. Further optimization of the configuration can also result to additional benefits.

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