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An alternative way to reduce fuel consumption during cold start: the electrically heated catalyst

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ABSTRACT

It is well known that the optimal management of cold start is crucial to fulfill present and future emission legislation. During past years the catalytic converter has left its original under floor position to get increasingly closer to the engine in order to exploit higher exhaust gas temperature. Simultaneously, the exhaust gas temperature is becoming significantly lower, both in gasoline engines due to the extensive use of turbo charging, and in diesel engines thanks to very high combustion efficiency and in some cases the use of two stage turbo charging. A well established way to reach the catalyst light-off temperature fast enough to fulfill emission limits consists of artificially increasing the exhaust gas temperature. This has the drawback of a higher fuel consumption which conflicts with the tight CO2 targets now required of the OEMs. This paper describes an alternative way to warm up the catalytic converter in a fast and efficient manner using the electrical heated catalyst (EHC) with only minor increases of fuel consumption. Additionally, the application of the electrical heated catalyst is very effective in combination with a hybrid vehicle where the EHC itself can be activated via energy recuperation thus increasing the total energy efficiency.

INTRODUCTION

The origins of the development of the electrically heated catalyst (EHC) go back to the time when the American ULEV legislation was introduced. There was only one way to ensure compliance with the dramatically tightened limit values, especially as far as hydrocarbon (HC) emissions were concerned, and that was through a definite reduction in the light-off phase of the catalyst. One possibility here was to heat the catalyst carrier electrically. A working group between the members of German automotive industry and Emitec was set up and the “EHC” was developed. It consists in a standard metallic substrate with an electrically heated section installed upstream. Initially, it was used for serial production in the Alpina B12 and subsequently in the BMW 750i [1, 2, 3, 4, 7]. In the meantime, however, alternatives such as both engine-based catalyst heating techniques and close coupled catalyst systems were developed, and these were preferred by automotive industry.

In recent years, in addition to compliance with the emissions limit values, the achievement of lower CO2 emissions and at the same time lower fuel consumption became a key development area. The subsequent and consistent rise in the efficiency of modern engines, primarily the diesel engine, is leading to a dramatic fall in exhaust gas temperature. This has now reached a level which, depending on the application, load conditions and emissions aftertreatment technology, makes necessary an “external” supply of energy in order to reach a fast light off of the catalytic system to achieve the level of effectiveness required for compliance with the emission limit values [5].

Considering the recent vehicle architecture (availability of electrical energy, energy recuperation etc.), the electrically heated catalyst offers an interesting alternative to purely engine-based catalyst heating strategy. However, it is necessary first of all to consider the question of energy efficiency i.e. how effectively the energy content of the fuel is converted initially into mechanical power and then into heat flux in the catalyst. The evaluation of this efficiency compared with conventional engine heating strategy is the main topic of the next section.

THERMAL BEHAVIOUR IN EMISSIONS SYSTEMS

As already mentioned in the introduction, the electrically heated catalyst, following a short serial production in spark injection engine applications, became redundant as a result of the introduction of engine-based catalyst heating methods. Therefore, in order to evaluate the energy efficiency of the two systems, an up-to-date spark ignition engine application has been selected. It is well known that the light-off time should be as short as possible in order to comply with emissions requirements, especially with respect to HC. In addition, the light-off temperature of a three-way catalyst (TWC) is usually higher than that of a diesel oxidation catalyst (DOC). This means that for a limited period of time a high level of energy needs to be supplied to the TWC to reach light-off. Normally no further heating measures are required once the catalytic converter is activated. Fig. 1 shows the temperatures upstream an underfloor catalyst with, and without, engine-based heating strategy and the resulting energy requirement.

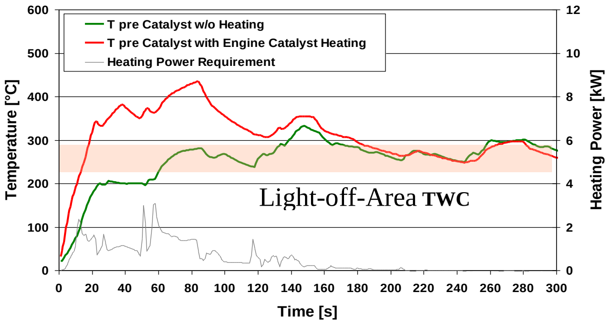


Fig. 1 : Temperatures upstream of catalyst on SI engine with and without engine-based heating measures.

Engine based catalyst heating strategies are usually carried out by artificially deteriorating the combustion process, for example in a gasoline engine using a late ignition point or, in a diesel engine a late injection. Since the resulting combustion is not very efficient then the exhaust gas temperature will be higher. A further strategy possible for DI gasoline engines and diesel engines consists of a particularly late injection in order to have unburned hydrocarbon in the exhaust gas and thus convert fuel energy into heat directly in the catalytic converter via an oxidation process. However, this strategy might increase raw emissions depending on the load point hence it can be only be used to a limited extent.

In order to boost the amount of energy supplied to the catalytic converter, the engine speed is also increased with a consequent increased mass flow through the engine and through the catalyst (in some cases it is almost doubled). This gives a significant acceleration in system heating albeit at the price of further fuel consumption increase.

Before the energy available in the exhaust gas, as higher mass flow at higher temperature, is transferred to the catalytic converter other parts of the exhaust line upstream of the converter (such as manifold, inlet cone, etc) will partly absorb it .

The energy portion absorbed by passive components (i.e. not actively taking part to the catalytic conversion) represents a net energy loss. Conversely, if the catalyst is electrically heated then the required amount of energy can be introduced directly at the catalyst thus avoiding losses to passive components. Moreover, an increase of exhaust mass flow is no longer necessary as the amount of energy needed is clearly reduced. However, in a worst-case scenario the electrical energy needed to heat up the EHC will be obtained from the mechanical energy of the engine dynamics, taking into account the corresponding levels of efficiency. Fig. 2 shows the principal energy flows using engine-based heating techniques as well as electric heating.

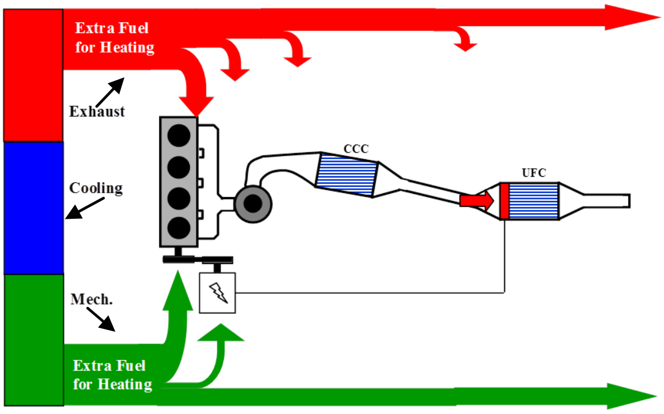


Fig. 2: Energy flows with engine-based heating and electric heating

In order to evaluate the specified losses, a direct-injected turbo-charged gasoline engine fitted with an under-floor catalyst has been examined.

ENGINE-BASED CATALYST HEATING

Fig. 3 shows the amount of fuel burned in the engine with, and without, catalyst heating (right Y-Axes) and the theoretical obtained energy (left Y-Axes) from the fuel with conversion efficiency of 100%. The efficiency of the catalyst heating strategy is on the other hand given by the ratio between the energy that actually reaches the converter and the theoretical quantity of energy available from the higher fuel consumption.

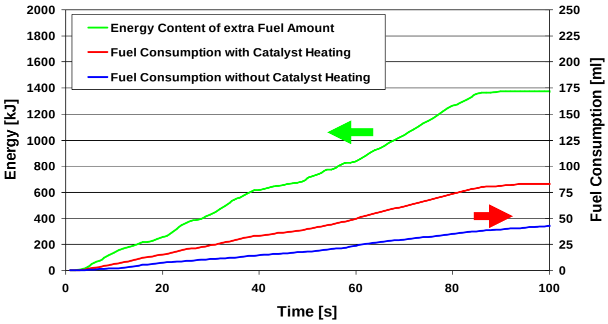
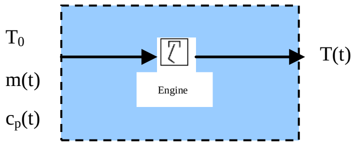


Fig. 3: Amount of fuel used and theoretical energy content in engine-based catalyst heating

In order to calculate this efficiency, the difference of exhaust gas energy at different positions in the exhaust system has been determined, based on the respective temperatures of the exhaust gas with and without the application of catalyst heating. In the case of engine-based heating the difference in the mass flows with, and without, the application of catalyst heating must also be taken into account.

The amounts of energy were observed over a period of 100s after starting the engine. The effects of heating the thermal mass in the engine and the exhaust system are also reflected in the result as energy losses.



$$Q_1 = \int_{t=0}^{100} \dot{m}_1 c_p(T)\left(T_1(t) - T_0\right)dt$$

$$Q_2 = \int_{t=0}^{100} \dot{m}_2 c_p(T)\left(T_2(t) - T_0\right)dt$$

$$\Delta Q = Q_1 - Q_2$$

Fig. 4: Calculation of exhaust gas energy based on mass flow and temperature

In Fig. 4 the index 1 refers to engine-based catalyst heating conditions, while index 2 refers to no engine-based catalyst heating.

Fig. 5 shows the amount of energy introduced into the exhaust gas using engine-based heating measures calculated using the exhaust gas temperature difference upstream of the turbo-charger. A comparison of the amounts of energy (theoretical energy from the fuel and energy used to heat up the manifold) shows that only around 40 % of the fuel burned in the engine is converted in temperature difference (dT) at the turbo-charger position.

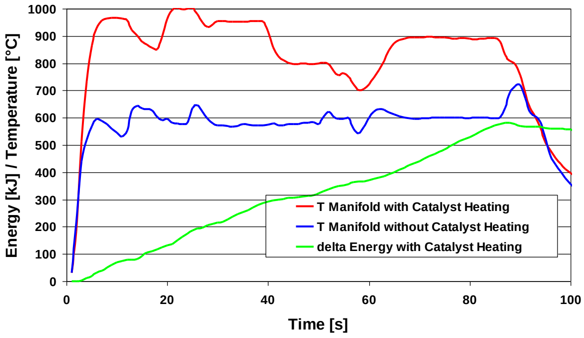


Fig. 5: Amount of energy upstream of turbo-charger introduced by the application of engine-based catalyst heating measures

The next stage of the work consisted in analysing the energy flow profile along the exhaust gas system; Fig. 6 shows the amount of energy in the pre catalyst position. It can seen that after 100s only around 300kJ have reached the catalyst, meaning that only about a quarter of the energy originally introduced is effectively used to heat up the catalyst. In addition there is the fact that a considerable portion of this energy has been used for heating the additional mass flow during engine-based catalyst heating. Fig. 7 shows the theoretical quantity of energy available (fuel) and the energy that reaches the manifold and the catalyst and hence the proportion of chemical energy introduced that actually arrives at the catalyst in the form of heat.

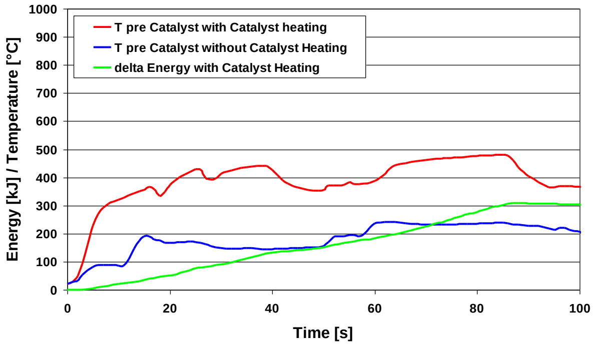


Fig. 6:* *Amount of energy pre catalyst introduced via the application of engine-based catalyst heating measures

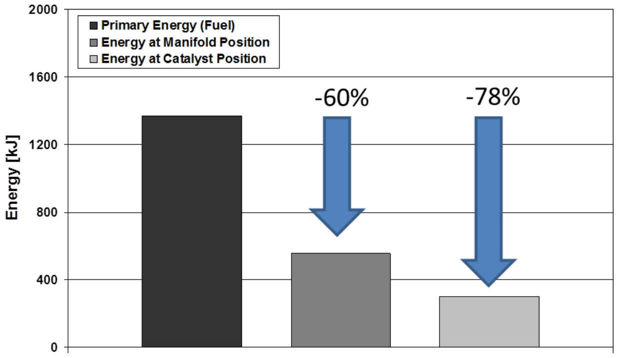


Fig. 7:* *Conversion efficiency for chemical energy into exhaust heat in energy-based catalyst heating within the first 100s

ELECTRICAL CATALYST HEATING

In order to ensure a real basis for comparison of the necessary heating energies, an EHC with a power of 1800W has been activated until the tailpipe emissions reach the same level as in the case of engine based heating strategy applied; in this case the EHC operating time was 80s. The relevant emissions are shown in Fig. 8.

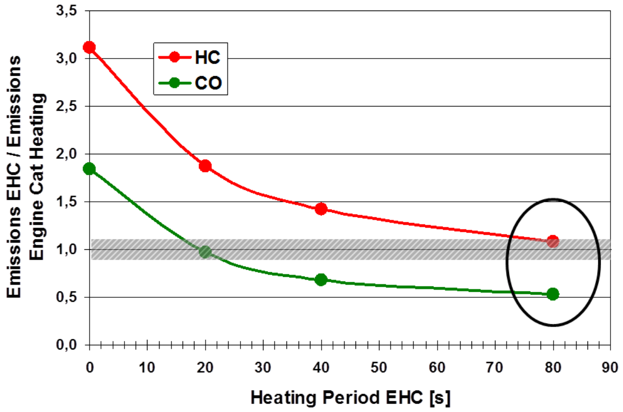


Fig. 8:* *Emissions ratio with engine-based catalyst heating and with heated catalyst as a function of heating period (1.8 kW)

In order to conduct an analysis of the necessary energy requirement to heat up the catalytic converter using the EHC a deep knowledge of the efficiency of the different components participating in the energy conversion is necessary. These are, on one hand the efficiency of the combustion engine itself i.e. the proportion of chemical energy that is converted into mechanical work and, on the other hand the efficiency of the electric generator in converting the mechanical energy into electrical energy. Both degrees of efficiency depend essentially on the load point under consideration and must therefore be available in the form of a map before a precise statement can be made. Additionally, any mechanical losses must also be taken into account. For this study a model has been used to simulate the entire vehicle structure including all efficiencies and losses which need to be taken into consideration. Simulation of the typical cases with, and without, engine-based catalyst heating shows an excellent correlation, which means that the results determined with electrical heating constitute a good assessment.

Fig. 9 shows the temperatures at the catalyst using the different heating processes. It can be noticed that a similar temperature level can be achieved using electric heating or engine-based catalyst heating even if the energy used in the EHC is much lower. This is predominantly the effect of the lower mass flow rate in EHC based catalyst heating than engine-based catalyst heating.

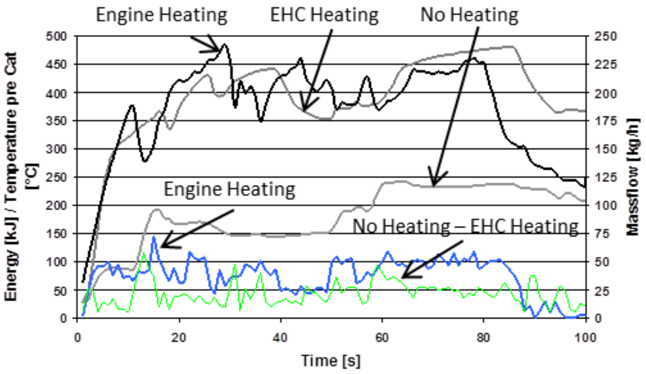


Fig. 9 : Temperatures and mass flows at the catalyst using a range of different heating processes

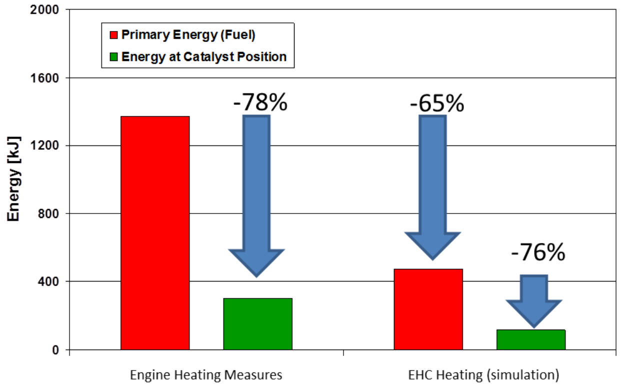


Fig. 10: Comparison of primary energy used and resulting energy at the catalyst in the first 100s for identical emissions level using both heating processes

This means that in engine-based catalyst heating the energy needed consists of two contributions: the first is the energy needed to heat up the mass flow from the temperature reached during normal operation to the desired temperature. The second is the energy needed to heat up the additional mass flow to the desired temperature. This second contribution is needed to heat up the catalytic converter as fast as possible. Therefore, in order to achieve a defined catalyst temperature, an energy level that is almost three times as high as with electric heating will be necessary (Fig. 10). A description of the simulation approach is provided in [6].

Thus, in the context of modern automotive architectures, the EHC appears particularly interesting from the energy requirement point of view.

Naturally, there is the question of cost. The complex design and manufacturing of the EHC causes higher substrate costs in comparison to a standard catalyst. Moreover, additional expense will be necessary for integrating the EHC in the electrical architecture of the vehicle. As a result of the clear increase in efficiency, however, potential for compensation may be found elsewhere, for example in relation to catalyst volume or precious metal loading. Finally, even the costs to reduce the CO2 emissions should be taken into account. Fig. 11 shows a comparison of system costs taking a passenger car DOC application as an example. The basis for the calculation is a DOC volume of 1.5 L with a load of 120g/ft³. For the EHC a volume of 1.2 l was applied as well as a reduced load of 80 g/ft³. These potentials have been derived from a number of measurements in relation to a range of applications. It is evident that, in addition to gains in terms of efficiency, the system also offers potential in regard to cost, particularly when the effect of savings in CO2 emissions as described in the previous section as well as their effect on any penalty tax that may be applied are taken into account.

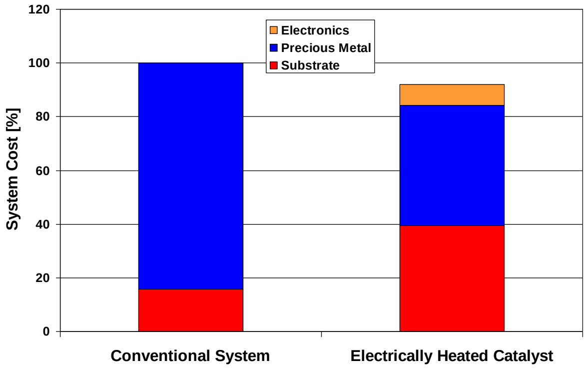


Fig. 11 : Comparison of system costs using a Passenger Car DOC as example

APPLICATION POSSIBILITIES FOR EHC IN THE DIESEL SECTOR

ELECTRICALLY HEATED DIESEL OXIDATION CATALYST

In diesel engines, the temperature level at the catalyst has been dramatically reduced due to the combustion efficiency optimization targeted at lower fuel consumption. Furthermore, due to the NOx optimised combustion process with high EGR, an increase of HC and CO engine out emission has taken place. This means that it is becoming increasingly more difficult to comply with the high requirements as far as HC and CO reduction are concerned, especially for cold start. On one hand, it takes a relatively long time for the light-off temperature of the catalyst to be reached; on the other hand, in dynamic operation the temperature consistently falls below the light-off temperature. The temperature difference for a significant efficiency improvement is in the region of 20 – 50K. Considering the mass flow in the NEDC, a very clear energy requirement can be derived that needs to be provided over a relatively long period, as shown in Fig. 12.

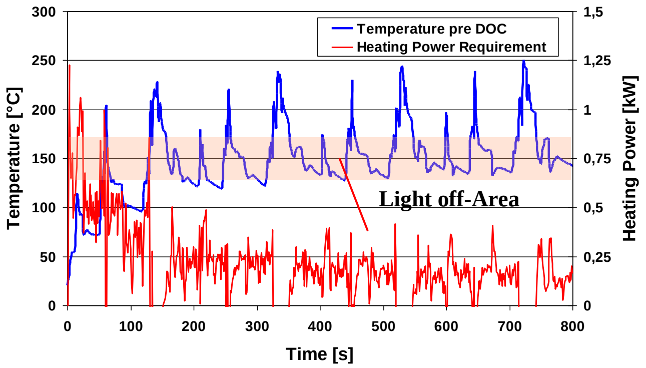


Fig. 12 : Example of temperature curve for diesel passenger vehicle in NEDC and energy requirement for achieving upper light-off temperature

It can be seen that a very high amount of energy is required to increase the exhaust gas temperature to the light-off temperature. Once the second hill is reached, the energy requirement is much lower (<< 1kW) to obtain the desired effect. Further application of heat will be necessary across the entire ECE to keep the temperature at the desired level, particularly in the idle phase. Due to this aspect, the modern vehicle architecture featuring integrated start-stop functions as well as brake energy recuperation in the deceleration phases offers enormous optimization potential regarding the generation of necessary energy.

With respect to the DOC application examined, a range of different heating strategies in relation to the resulting additional consumption, as well as influence on the emissions, were compared. At the same time both the start point for the electrical heating and its duration were varied. In addition, heat was applied on a localized basis in the deceleration phases in order to prevent any cooling of the substrate. In this instance it was not possible to give consideration to any start-stop function; we shall be looking to do this in future studies.

- 0-200 s (basic strategy)
- 0-60s
- 60-120s
- 60-120s + heating in deceleration phases (complete ECE)

Fig. 13 shows the temperature curves in relation to the pre cat temperature as well as matrix temperature 5mm in the catalyst matrix downstream of the heating slice with the various heating strategies.

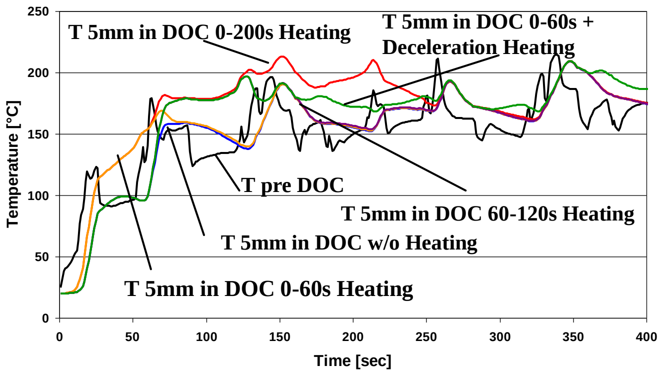


Fig. 13: Temperature curves in catalyst matrix with the different heating strategies

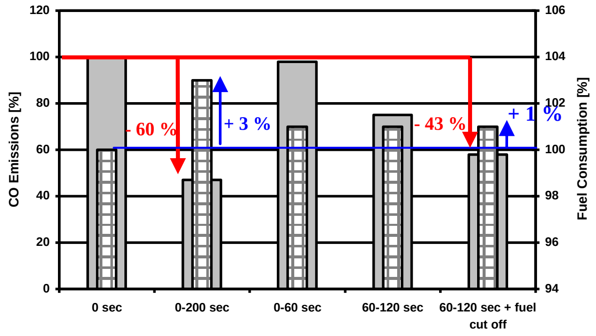


Fig. 14: Effect of the different heating strategies on CO emissions and fuel consumption (calculated on the basis of energy requirement)

Keeping the OEM's original engine calibration and using the initial strategy of heating from the zero up to 200s, CO emissions can be reduced by approx. 60%; however, this also results in an additional fuel consumption of around 3%. As the test featuring a heating time of 0-60s shows, in this period practically no improvement in emissions has been achieved because it is not possible to reach light-off temperature at a significantly early stage due to the high energy requirement of the catalyst. If we use the same heating period but start at 60s, a considerably enhanced effect can be achieved, plus there is the possibility of further improvements by follow-up heating during the deceleration phases. All this can be achieved without any additional fuel consumption with the help of recuperated energy. The result of this first optimization shows that is possible to reduce CO emission by 43% with a fuel consumption penalty of 1%.

A typical situation in which the low temperature creates problem is low load operation, for example the city cycle. Fig. 15 shows the temperatures of a light duty vehicle with an SCR system in the Artemis City Cycle (urban), where an electrically heated hydrolysis catalyst is located upstream the SCR catalyst i.e. normally the heated pre catalyst temperature would be the SCR inlet temperature. At the same time, the heating strategy has been selected in order to ensure that extra heat is only added to an exhaust temperature of 180°C, thus ensuring that the temperature in the SCR catalyst can be kept at a relatively constant level. Therefore, even under these conditions, very good NOx conversion has been reached. The use of start-stop functionalities could further increase efficiency.

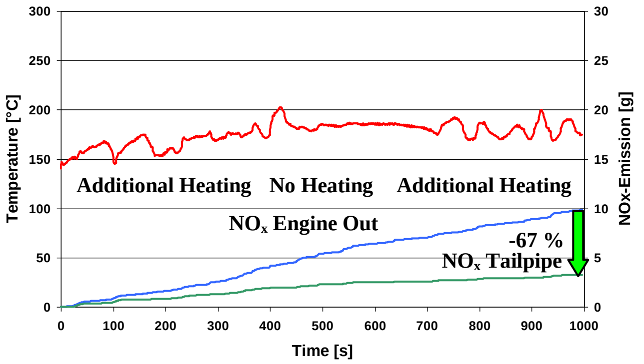


Fig. 15 : Temperatures and NOx emission with heated SCR system in the Artemis Urban Cycle

It is known that, even at temperatures below 180°C, the SCR catalyst achieves NOx conversion efficiency where sufficient ammonia is stored in the coating. The supply of ammonia, or the injection of AdBlue, is possible starting from a minimum temperature (between 160 and 180°C) in order to ensure appropriate vaporization, preparation and hydrolysis. In order to have a minimum efficiency even at low load phases during driving condition similar to the first 300s of the Artemis Cycle, without a high energy requirement to heat up the entire exhaust system, it is possible to inject AdBlue during idling phases with an alternative strategy. The low mass flow during idle leads, with the same power from the heated catalyst, to higher temperatures of the exhaust gas and the EHC itself. This ensures that the AdBlue injected can also be vaporized and prepared, even at the low exhaust gas inlet temperature. Fig. 16 shows a comparison between gas and heated element temperature for a range of different load points. It can be seen that, even with a relatively low power of 1 kW, a temperature in the range of 200°C can be achieved at the heated element and the exhaust gas, whereas, during normal operation, only very small differences in temperature can be generated.

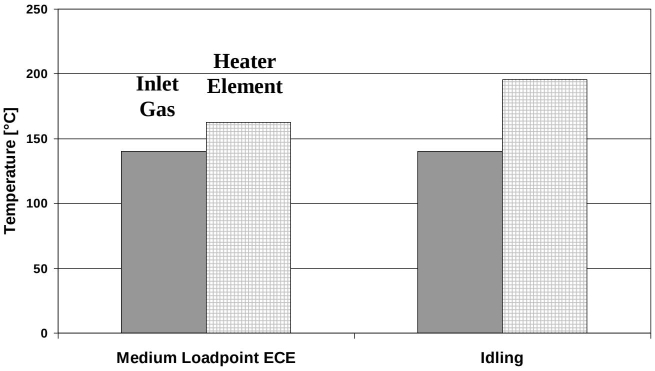


Fig. 16 : Achievable increase in temperature using electric heating at different load points

SUMMARY AND CONCLUSIONS

Despite its age, the electrically heated catalyst is proving to be thoroughly modern because it represents an ideal supplement to the current vehicle concepts featuring energy recuperation and start-stop functioning. By optimum coordination of the different functionalities and operating parameters it is also possible, with the electrically heated catalyst, to achieve effective thermal management even in terms of energy efficiency. Compared to conventional engine-based catalyst heating the EHC shows many advantages such as local energy delivery, short response time and good control with independence from engine load point. As a consequence new heating strategies, in particular even for SCR Systems, can be adopted. The optimization of the strategy and the investigation of potential further energy saving will be the aim of future studies.

Another key point is the self-financing integration of the heated catalyst in the overall exhaust after-treatment. An intelligent approach needs to be adopted which could consist, for example, in the reduction of precious metal loading or the achievement of savings in fuel consumption.

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