ABSTRACT

Further advancements in engine development lead to increased fuel efficiency and reduced CO₂ emission. Such low emission engine concepts require most advanced exhaust gas after treatment systems for lowest possible tailpipe emissions. On the other hand, the exhaust gas purification by catalytic measures experiences more and more challenges due to constantly reduced exhaust gas temperatures by more efficient engines. These challenges can be overcome by traditional catalyst heating strategies, which are known to increase fuel consumption and emissions. Alternatively, electrically heated catalysts (“EHC”) can be utilized to provide a very efficient method to increase gas temperatures directly in the exhaust catalyst. This way the energy input can be tailored according to the component need and the energy loss in the system can be minimized. This advanced path of thermal management looks especially attractive considering increasing electrification of vehicles and utilizing more recuperative energy recovery practices in new vehicles. Depending on the application, electrically heated catalysts can give overall energy and emission benefits. The work in this paper describes the technology needed for direct exhaust gas temperature management with electrically heated catalysts and presents results for different applications in comparison to traditional engine heating measures.

INTRODUCTION

Continuous improvements of internal combustion engines have led to increased fuel economy and corresponding lower CO₂ emission [1]. Improved combustion efficiency and reduced losses have also caused exhaust gas temperatures to decrease, generally leading to greater challenges for the exhaust gas after treatment system. This naturally leads to the need for thermal management of exhaust temperatures, which has traditionally been accomplished with an engine internal strategy. When ULEV legislation was introduced, for gasoline engines this caused a large challenge leading to consideration of alternative technologies such as an electrically heated catalyst. In summary the California ULEV legislation required a distinctive reduction in catalyst light-off temperature, especially for hydrocarbon (HC) emissions, to comply with the drastically stricter emission limits. One potential solution was the utilization of electrically heated catalyst. This has led to a joint development of a working group of members of the German automotive industry and Emitec, and the EmiCat catalyst (EHC – electrically heated catalyst) with its electrical heating capability has been developed. Initially, it was used in volume production in the Alpina B12 and subsequently in the BMW 750 i [2, 3]. However, the volume production of the electrically heated catalyst has been rather low, since alternatives like engine-based catalyst heating were developed and replaced the usage of the EHC.

Recent developments focusing on higher fuel efficiency and lower CO₂ emissions have taken highest priority for latest engine advancements. The corresponding efficiency increase of modern engines, primarily diesel, leads to distinct decrease of exhaust temperatures. Depending on the application, the drive cycle and the after treatment technology, the exhaust temperatures have reached levels which require additional energy delivery directly into the exhaust system in order to comply with the required emissions levels [4]. Since current vehicle developments look intensively at hybridization and electrification, the foundation to apply electrically heated catalyst has been significantly changed in favor of such devices. Also required surrounding electronics have been developed to mature stages to support thermal exhaust gas management via heated catalysts. Nevertheless, the energy efficiency utilizing the EHC has to compete and outperform traditional engine based exhaust gas heating to be a rational choice. This has been evaluated in detail in this paper.
ELECTRICALLY HEATED CATALYST

The goal of the initial development of the electrically heated catalysts was fast light off of catalytic activity even under very difficult cold start conditions, i.e. at very low exhaust gas temperatures. Since the crucial factor for this activity is the temperature of the catalyst rather than that of the exhaust gas, the design focused on ensuring that as much of the available electric power as possible has been used to increase temperature of the heater element and consequently the metallic catalyst.

Thus, the actual heater was designed as an integral part of the catalyst in the form of a honeycomb disc in the catalyst inlet. This directly heated disc also has a catalytic coating, which allows it to start converting pollutants immediately. The disc is mechanically supported by the second part of the catalyst, the support catalyst. This catalyst and other downstream (after) components are heated by the exhaust gas, which has been heated by the disc.

The disc works on the principle of a heating coil. Power is supplied at one end by an electrical connection, which conducts electricity to the foil packet via a half shell. The resistance of the foil packet itself determines the electric power of the heated catalyst. Like the normal winding process of the metal matrix, the disc receives its specific form by being wound into an S shape. Contact with the vehicle ground is provided by a second half shell, which is usually connected to another section of the catalyst jacket or via a separate contact.

An air gap prevents short circuits inside the heated disc and ensures that power flows through every part of it. The heated disc is mechanically supported by insulated pins that are brazed to the heated disc and the support catalyst. This construction ensures that the catalyst is able to permanently withstand the high thermal and mechanical loads in the exhaust system [5].

EXHAUST GAS TEMPERATURE MANAGEMENT

As described above, the electrically heated catalyst has been used in spark ignition engine applications in the past, but quickly became redundant as a result of the introduction of engine-based catalyst heating methods. To evaluate the energy efficiency of the electrically heated catalyst, such system has been compared to a state of the art spark ignition engine application.

If engine-based exhaust gas temperature management is utilized, deterioration in combustion efficiency can be artificially brought about by applying a range of different parameters. Examples of these parameters are ignition timing in the case of a petrol engine or the injection timing for diesel engines. The target is to generate higher exhaust gas temperatures. A further course of action is the deployment of particularly late stage injection in order to bring about combustion in the exhaust gas and thus to convert the energy in the fuel into heat. Depending on the load point, this measure can also lead to increased raw exhaust gas emissions and is limited depending on the existing constraints. In order to boost the amount of energy supplied even further the engine speed is also increased and at the same time the mass flow through the engine and through the catalyst receives a significant boost, it can almost be doubled in some cases. This means, on the one hand, a definite acceleration in system heating and, on the other, a further increase in the amount of fuel required to achieve a specific temperature level. The increase in exhaust temperature has to be transported to the different catalysts. The position and, with it, the thermal mass of the upstream (before) components will therefore play a crucial role, particularly when it comes to cold starts.

By comparison, when the catalyst is electrically heated, the energy can be introduced directly at the catalyst, which means that the losses mentioned above can be avoided. Moreover, all that needs to be heated is the mass flow that is actually required for operation of the engine and to provide the necessary drive power and this clearly reduces the energy requirement. However, in a worst-case scenario, the electrical energy will need to be reclaimed from the mechanical energy of the engine via the generator, 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.

CATALYST HEATING: ENGINE-BASED

In order to evaluate the specified losses, a light duty passenger car application featuring a direct injection, turbo-charged SI engine fitted with an under-floor catalyst was examined [8]. As a rule, a spark ignition engine behaves in such a way that the catalyst needs to be catalytically active after a very short time in order to comply with the emissions requirements, especially in regard to HC. In addition, the Light-Off temperature of the three-way catalyst (TWC) is activated at a significantly higher level 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 catalyst. Normally no heating measures are required later in the cycle. Fig. 3 shows for a SI engine example the temperatures upstream of the catalyst with and without engine-based heating measures, as well as the resulting energy requirement during a cold start (cold catalyst). The heating is activated during the first 80 seconds. The max. heating power requirement amounts to 2-3 kW.
Figure 2 - Energy flows with engine-based heating and electric heating.

Figure 3 – Exhaust gas temperature upstream three-way-catalyst of a spark ignition engine with and without engine-based heating measures during cold start.

Fig. 4 shows the amount of fuel consumed as well as the corresponding theoretical energy content of the fuel without any losses at 100% efficiency. Of relevance for cold start is, however, the amount of energy available within a specific period of time in the component to be heated up. The degree of efficiency based on a comparison of the two amounts of energy reflects the efficiency of the catalyst heating measure as regards to the amount of fuel used. For this comparison, the difference in exhaust gas energy at different positions in the exhaust system was 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.

Figure 4 – Engine based catalyst heating: fuel used and theoretical fuel energy content.

An energy balance / comparison has been performed over an initial cold start period of 100s. The effects of heating the thermal mass in the engine and the exhaust system are also reflected in the result as temporary losses. Fig. 5 shows the amount of energy introduced into the exhaust gas using engine-based heating measures. This relates to the comparison of the exhaust gas temperatures upstream of the turbine. A comparison of the amounts of energy in Fig. 4 and Fig. 5 shows that only around 40 % of the fuel used demonstrates a temperature difference (dT) on arrival at the upstream turbine position. The remaining 60% of incremental fuel consumption do not support acceleration in catalyst light-off. They mainly contribute to temperature losses in the engine and the exhaust manifold. They also lead to increased cold start emission.

Figure 5 – Temperatures upstream turbine with and without engine-based catalyst heating and corresponding effective energy amount calculated upstream turbine.

After considering the energy balance upstream turbine, the next stage is to investigate how the flow of energy behaves in the remainder of the exhaust gas system. Fig. 6 shows the amount of energy as a time-dependent factor in the pre catalyst position. It will be noticed that,
after 100s, only around 300kJ have arrived at the catalyst. This means that, of the energy originally introduced, only about a quarter is effectively used for heating the catalyst. In addition there is the fact that a considerable proportion of this energy has in turn to be used for heating the additional mass flow during engine-based catalyst heating. Fig. 7 shows the corresponding energy losses en route from fuel to catalyst and hence the proportion of chemical energy introduced that actually arrives at the catalyst under consideration in the form of heat.

CATALYST HEATING: ELECTRICALLY

In comparison to the above described engine-based catalyst heating, an electrically heated catalyst (EHC) has been tested for this work similarly utilizing a light duty passenger car application featuring a direct injection, turbo-charged SI engine fitted with an under-floor catalyst [8]. The EHC has been designed to have an electrical input of 1800 W. These 1800 W have been applied to the electrically heated catalyst while the engine-based catalyst heating had been disabled. The corresponding emissions have been measured and compared to the case with engine-based catalyst heating. As expected, initial emissions without engine-based catalyst heating are higher compared to with heating. However, utilizing the 1800 W electrical power directly introduced to the catalyst reduces the emissions considerably. The amount of emission reduction improves with electrical heating duration. Figure 8 shows the results for HC and CO emissions as the ratio between emissions with EHC on and emissions with engine-based catalyst heating vs. time of EHC on. It can be noticed that with electrical catalyst heating the same tail pipe emissions were achieved as with the conventional catalyst heating strategy for a heating period of approx. 80 seconds for HC and only 20 seconds for CO.

Figure 6 - Temperatures upstream catalyst with and without engine-based catalyst heating and corresponding effective energy amount calculated upstream catalyst.

Figure 7 – Fuel energy conversion efficiency for engine-based catalyst heating; SI-engine; first 100s after cold start.

Figure 8 – HC- and CO-emissions ratio of emissions with electrical heating and engine-based heating as a function of heating period at 1.8 kW electrical power.

If we conduct a similar study of the energies necessary for electric heating, a precise knowledge of the degrees of efficiency involved will be necessary. This is, on the 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, the efficiency of the 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. In addition, any line losses must be taken into account. For this energy study a simulation model was used that illustrates the whole of the vehicle structure with all efficiencies and losses that need to be taken into consideration [8]. Simulation of the typical cases with and without engine-based catalyst heating showed an excellent correlation, which means
that the results determined with electrical heating should constitute a good assessment.

Fig. 9 shows the temperatures at the catalyst using the different heating processes. In essence, a similar temperature level can be achieved using electric heating to that achieved with engine-based catalyst heating, although the required energy input is significantly lower. This is predominantly the effect of the lower mass flow by comparison to the variant with engine-based catalyst heating.

![Figure 9 – Mass flow and pre-catalyst temperatures for engine-based and electrical catalyst heating.](image)

This means that in engine-based heating by comparison to unheated operation it is not only the temperature difference (dT) that has to be taken into account, but in addition the additional mass flow will need to be heated up completely. 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. This finally culminates, with comparable efficiencies, in the need to use up to 2/3rds less primary energy as illustrated in Figure 10.

![Figure 10 – Primary energy used and resulting energy at the catalyst position in the first 100s after cold start resulting in similar emission levels using both heating processes.](image)

Thus, in the context of modern automotive architectures, the electrically heated catalyst appears both energetic and thoroughly practical. Naturally, there is the question of cost. To begin with, the complex design and manufacture of the EHC entails higher substrate costs by comparison to the standard catalyst. Moreover, additional expense will be incurred for integrating the EHC in the electrical architecture of the vehicle. As a result of the clear increase in efficiency, however, potential for cost compensation may be noted elsewhere, for instance in relation to catalyst volume or precious metal loading. Ultimately, there is also a need to counterbalance factors that affect CO₂ emissions as a result of system optimization. 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 120 g/ft³. For the EHC a volume of 1.2 L was applied as well as a reduced load of 80 g/ft³. These potentials were 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, in particular 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.

![Figure 11 – Conventional DOC vs. DOC with integrated electrical heater: system cost comparison for a passenger car example.](image)

**ELECTRICALLY HEATED CATALYST IN DOC POSITION: APPLICATION EXAMPLE I**

For the application examples of the electrically heated catalyst, a 3-liter Diesel engine has been utilized. The temperature potential of the passenger car engine has...
been tested initially performing tests with the serial production Euro 5 system. The system utilizes a DOC, a DPF, and an SCR system. Temperatures in the DOC, downstream DPF and upstream SCR were measured during the new European Drive Cycle and are plotted in Figure 12. It took approximately 150 seconds to reach a minimum DOC light-off temperature of around 170°C for HC and CO conversion. Looking at the temperatures upstream SCR, as shown in Figure 12, it takes additional 370 seconds (total of approx. 520 seconds) to reach a similar temperature of 170°C in that position. The SCR catalyst temperature is essential for the DEF dosing release and a gas temperature of 170°C does not necessarily correspond to dosing start. This depends on utilized SCR catalyst technology as well as required NOx conversion. It shows however, how much potential to increase NOx conversion such applications offer by applying smart heating strategies.

Figure 12 - Exhaust gas temperature history in the DOC, downstream DPF and upstream SCR catalyst for a 3 ltr. diesel engine in NEDC.

After the above described base system measurements, an electrically heated catalyst has been added to the system in the upstream DOC position (heating disk integrated into DOC). The electrically heated catalyst used 1 kW electrical energy and has been switched on for the first 100 seconds of the NEDC. This means, the current has been applied for 100 seconds. Then the electrical power has been switched off but the remaining heat in the heating disk is still utilized. The temperature effect of utilizing the EHC in a DOC position with consuming 1 kW for 100 seconds has been measured in similar positions as described above and is shown in Figure 13. The light-off temperature, which has been reached after approx. 150 s without heating, could be reached approx. 100 s earlier, providing significant advantage in HC and CO emissions, about 25% and 60%, respectively. Also in the downstream DPF position the 100 seconds of “EHC on” have a significant effect. A temperature of 170°C is reached approx. 80 seconds earlier than in a system without electrical heating as shown in Fig. 13. However, in the upstream SCR position the heating strategy described above had no advantage at or above 170°C. This is caused by the thermal mass of the DOC and DPF and the configuration (mixing section) of the SCR system downstream DPF. However, a different heating output and/or heating strategies (start, duration, activation at specific intervals during idling and/or deceleration) are expected to have significant potential with regard to the SCR temperature and hence the dosing release/strategy.

In addition to the temperature results shown in Fig. 13, the effect on NO\textsubscript{2} formation within the DOC has been investigated and the results are shown in Figure 14. Here, two different heating strategies were applied. Similarly as described above, first 100 seconds of electrical heating have been considered and second 250 seconds of “EHC on” have been measured. The results in Fig. 14 show that substantially higher NO\textsubscript{2} formation performance could be measured utilizing the electrical heating in the 150 to 350-second range. This could improve the efficiency of the SCR reaction (fast SCR reaction), provided that the required minimum temperature has been reached. This effect was due to the electrically heated catalyst alone.
ELECTRICALLY HEATED CATALYST IN SCR POSITION: APPLICATION EXAMPLE II

After obtaining very promising results with an electrically heated catalyst in DOC position as described above, later additional testing has been performed with an electrically heated SCR system. Since SCR systems in passenger cars are very complex, especially with regard to the number of different components and the way they interact [6, 7], the system needs to be described somewhat more detailed compared to the DOC position: SCR systems are usually fitted in the underbody position downstream of the DOC and DPF, the disadvantages of having to heat the exhaust system and its components become particularly evident. Therefore, electrical heating of the SCR catalyst or an upstream hydrolysis catalyst seems promising. Here, the electrically heated catalyst has been integrated in a hydrolysis catalyst with an upstream DEF injection and an electrical power of 1.9 kW. Further upstream are the DPF and the DOC. The DEF injector sprays directly on the electrically heated hydrolysis catalyst with the SCR catalyst further downstream. All system components and the configuration of the system are shown in Figure 15.

The system shown in Fig. 15 has been used for testing at especially low loads, such as urban cycles. Figure 16 shows the exhaust gas temperature results for the Artemis Urban Cycle of the 3.0 ltr. diesel engine in a delivery van. In this example an electrically heated hydrolysis catalyst was fitted upstream of the SCR catalyst as described above. Usually, the temperature before the heated catalyst would correspond to the SCR inlet temperature. The selected heating strategy was to provide heating until the exhaust gas temperature reached 180°C, thus keeping the temperature in the SCR substrate at a relatively constant level. Even under these very challenging conditions for SCR systems, good NOx conversion rates of 65-70% could be achieved thanks to the temperature increases caused by electric heating. The SCR catalyst system achieves significant NOx conversion rates even at temperatures below 180°C as long as sufficient ammonia is stored in the coating. However, the supply of ammonia or the injection of DEF requires a minimum temperature (between 160 and 180°C) to ensure evaporation, preparation and hydrolysis. This is the area where the electrically heated hydrolysis catalyst opens additional potential to increase NOx efficiency. In addition to the performed tests, additional potential seems possible with the utilization of a start/stop function.

The results shown in Fig. 16 represent a system in under-floor position, which is typical for current applications due to package and mixing constraints. For future systems the SCR catalyst is believed to move toward the engine in a close coupled position to the DPF. The temperature history and the cumulative NOx raw emissions from a 3.0 ltr. engine in LD application (see Fig. 15) are shown in Figure 17. These data represent the basis for an estimate of the potential that could be developed by an SCR catalyst installed closer to the engine combined with additional electric heating in a DOC position.
Figure 17 shows that the temperatures downstream DPF with electrical heating could allow DEF dosing approx. 80 seconds earlier compared to without heating. In addition, moving the SCR catalyst directly downstream of the DPF (initially disregarding the requirements of effective ammonia injection and distribution), would allow for another approx. 150 seconds of earlier DEF dosing. The initial 80 seconds are in fact only possible if the SCR is moved upstream, since the gained temperature through electric heating during the first 100 seconds now to a large extent also arrives at the SCR substrate due to lower heat loss. By this the EHC is able to produce another reduction of 20% of nitrogen oxides. In this example, moving the SCR catalyst upstream and applying electrical heating for 100 seconds, both would reduce cumulative tailpipe NOx emissions by approx. 20% each. The total of additional 40% NOx reduction represents a high potential and will be investigated in the next steps of this work.

The results from this work show significantly reduced cold start durations to achieve catalyst light-off temperatures and corresponding lower tailpipe emissions. They demonstrate potentially improved overall energy balance for electrically heated catalysts in comparison to engine-based catalyst heating. With just 100 seconds of heating with a 1 kW electrically heated catalyst in DOC position approx. 100 seconds earlier light-off can be achieved with significant advantage in HC and CO emissions, about 25% and 60%, respectively. Also the NOx formation can be improved leading to optimized SCR NOx reduction efficiency. For a more complex SCR system, very good NOx conversion efficiencies could be achieved with an electrically heated catalyst in the hydrolysis catalyst position. Even with very low engine out temperatures, DEF dosing could be activated due to catalyst heating. For future SCR systems moving towards the engine or close to the upstream DPF, approx. 40% NOx conversion efficiency improvement potential could be identified. Approx. half of this improvement (20% NOx reduction) would be provided due to higher temperatures directly closer to the DPF and the other half (20% NOx reduction) could be achieved due to electrical (catalyst heating).

SUMMARY AND CONCLUSIONS

Electrically heated catalysts have been used for quite some time already. However, high volume application has always been limited due to cost and complexity. Now the electrically heated catalyst seems more viable and modern than ever before considering increasing electrification of vehicles and utilizing more recuperative energy recovery practices and start/stop functioning. The EHC enables effective exhaust gas thermal management. In comparison to traditional engine-based catalyst heating, depending on application and operating parameters multiple advantages can be observed. These include local, targeted inputting of energy, short control paths and hence short response times and good controllability. This can be achieved with much more degree of independence from the adjacent engine operation point compared to traditional catalyst heating. From an energy prospective, the electrically heated catalyst can show a better overall efficiency and hence provide fuel savings as well as reduce emissions from traditional engine-based catalyst heating such as PM from direct injection gasoline engines. For gasoline three-way-catalysts (TWC) as well as for diesel oxidation catalysts (DOC) and selective catalytic reduction systems (SCR), new heating and control strategies can be considered. From a product cost prospective, the additional cost of an EHC can potentially be compensated by reduction in needed catalyst size or PGM utilization. Also fuel efficiency improvements and CO2 emission reduction can compensate for product cost, especially considering CO2 emission tax and taking an overall holistic viewpoint.

REFERENCES

1. T. Johnson, SAE 2011-01-0304

6. P. Spurk, M. Pfeiffer, F.-W. Schuetze, Umicore AG & Co. KG; CTI-Abgastechnik, Januar 2007: “Anforderungen an den DOC & DPF in Dieselabgasnachbehandlungssystemen mit NOx Nachbehandlung”


CONTACT INFORMATION

Dr. Ulrich Pfahl
Chief Engineer
Emitec, Inc.
Emissions Technology
3943 W. Hamlin Road
Rochester Hills, MI, 48309
USA
Phone: +1 248 276-6442
Email: ulrich.pfahl@emitec.com

ACKNOWLEDGMENTS

We thank our colleagues at Continental for assisting with vehicle measurements and simulation of energy balances.