Innovative and cost-effective Exhaust After Treatment for LEV Tier IV emission legislation

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Abstract. The future of the internal combustion engine (ICE) depends essentially on the ability to adapt enough with sustainable products. This means to minimize its impact on the environment regarding gaseous pollutants and particulates. Even more, a significant reduction of CO_2 emission e.g., by a possible use of electrified powertrains and, in addition, the ability to run with CO_2 free fuels are needed.
The first aspect regarding tailpipe emissions must be treated not only considering purely the technical feasibility, but also considering the add on system costs necessary to reach the lowest emission limits. It has been shown in a previous work, that the use of an Electrically Heated Catalyst or Electrically Heated Disk can help to reach a more efficient Exhaust After-Treatment System.
PHEV vehicles represent one of the solutions to reduce CO_2 and are also enabling some of the obstacles for usage of an electrical heated catalyst. PHEV vehicles have a unique challenge regarding cold start emissions due to sudden torque demands when the electrical propulsion suddenly needs power support. This study focuses on the challenge and discusses PHEVs unique possibilities to pre-condition the catalytic converter.
The objective of this paper is to investigate the system design aspects regarding the possibility of the development of state-of-the-art auxiliary air injection with the Electrically Heated Disk (EHD) to minimize gaseous pollutants emission, in particular during cold start, and to keep the exhaust after treatment cost at a reasonable level. Auxiliary air is used during pre-heating to warm up a certain volume of the catalyst above light off temperature to have almost zero cold start emissions. The duration of the pre-heating is a key parameter both for customer acceptance, considering that the ICE can't be started, and energy management.
To assess the efficiency of a new exhaust after treatment, the coming LEV IV regulation has been chosen, where the new US06 cold test cycle has been investigated. It represents one of the future requests for LEV IV legislation for PHEV vehicles. Vehicle tests has been carried out to collect data and was combined with engine test bench measurements. The engine test bench was used to increase test repeatability and reduce cooling time between consecutive tests.
As a result, the reduction of pollutant emissions to a very low level, while keeping the system cost at an acceptable level, will be presented.

Keywords: Exhaust Aftertreatment for PHEV, Pre-heating, High Power Cold Start Emissions.

1 Introduction

Large scale vehicle electrification is expected to play an important role in eliminating fossil fuel dependency. However, although battery electric vehicles eliminate tailpipe CO_2 emissions, up- and downstream emissions connected to battery manufacturing and recycling represents a major challenge. Therefore a “cradle-to-grave” perspective trough a Life Cycle Analysis (LCA) protocol becomes increasingly important [1]. In a plug-in hybrid vehicle (PHEV), low utilization batteries of BEVs are replaced by an ICE resulting in lower zero mileage CO_2 footprint and, depending on utility factor, significantly lower CO_2 emissions per km than a conventional ICE vehicle. The differences in operation scheme of the ICE in a PHEV versus in a conventional ICE vehicle does however require specific attention to hazardous emissions.

The research regarding SI ICE is mostly focusing on the cold start, considering that emissions in warmed up conditions are very close to zero. Cold start conditions are mainly defined by the catalyst heat up phase, where most of the engine out emissions pass through the catalyst untreated and are then released into the atmosphere. One typical goal of the researchers for all ICE applications (not just PHEVs) is to find ways to decrease the time for the heat up phase of the catalyst to a minimum. One possible solution to accomplish this, is to use an Electrically Heated Catalyst [2] or Disk [1, 3] to heat up the catalyst during a number of seconds after the engine cranking or even before the cranking starts itself.

Another important aspect to consider, is that after engine cranking, the idling time will be reduced or even eliminated in the Emission Legislations being enforced in the coming years. The reduction of the idling time may have a massive impact on the tailpipe emissions [5, 6] and on the system layout. Moreover, the possibility to apply high loads on the engine right after the cranking, has the consequence that the catalyst volume above light off temperature must be increased. This is needed to treat the higher mass flow rate, compared to common case.

For those cases in particular, the active heating has massive benefits when it is coupled with auxiliary air (AAI). This is to transfer as much of the generated heat as fast as possible from the heating disk to the catalyst behind the active heating itself.

This paper investigates pre-heating strategies in combination with the introduction of AAI, primarily in a PHEV context. The starting point for the discussions is the future legislation and a PHEV use-case approach. The PHEV use-cases depend on a combination of electrical and ICE propulsion and therefore differ a lot from ICE only use-cases. The paper continues to discuss the unique packaging challenges with PHEV and what impact this has on EATS design. This then leads to the introduction of emission system design with EHD as active heating and AAI. After this, the realization of emission tests using this design and methods for evaluation are discussed. The result chapters towards the end are divided into two parts, where the first presents the emission test results and the latter part discusses methods and results and deals with how to design and evaluate AAI flow conditions with a closed coupled catalyst.

2 Development in US legislation regarding PHEV

A paper from CARB [4] highlighted the unique emission challenge for PHEVs during customer operation that was then named high power cold start (HPCS). In the investigation CARB defined five different versions of highway entrance ramp-up accelerations. Three different PHEV vehicles at that time available on the market were tested for the various HPCS challenges. The different vehicles behave differently as a consequence of the available power from the two different propulsion system, electrical and ICE. All vehicles have an emission challenge when the propulsion system switches to the ICE system with a sudden engine start combined with a direct high-power demand.

In the proposed upcoming LEV IV legislation CARB has updated its legislation including PHEV to consider the HPCS challenge. For HPCS the new PHEV updates means that the so called US06 cycle should start with a cold vehicle (+23° C) and full SOC level. Considering that the US06 includes higher power demand, it can be possible that the ICE has cold start with direct high load. Depending how the vehicle is designed and calibrated this challenge for the vehicle can be more or less severe.

Other proposed updates for PHEVs regard the strict rules that define what type of vehicle can qualify as a ZEV: BEVs of course, and certain PHEVs with minimum all electric range (certification range value of greater than or equal 70 miles). In addition, PHEVs which qualify for ZEV status must be certified to SULEV 30 or lower emission standards, have extended warranty (15 years, 150,000 miles), certain battery labelling and warranty requirements, and have a minimum US06 all-electric range of 40 miles. The PHEV portion of the total ZEV requirement is capped at 20% of each vehicle manufacturer’s production. On this paper we exclude considering potential ZEV benefits.

To investigate this challenge with regards to catalyst systems, Aurobay used a Volvo PHEV test vehicle. Various calibrations of the engine and vehicle software were introduced, which altered the control and balance of energy and torque from ICE and electric motors. This enabled different variants of sudden ICE cold starts during the US06 cycle. The first vehicle test campaign resulted in 10 different variants. They have all different behaviors in ICE usage in the cycle. This of course results in different emission challenges as can be seen by 4 examples in Figure 1.

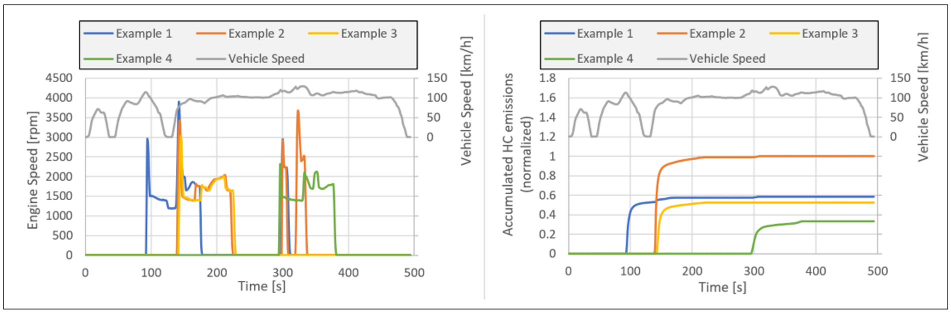


Fig. 1. Four examples of PHEV applications, US06 with different ICE HPCS behavior.

3 Case Study with PHEV Vehicle

3.1 Cold Start Use-cases

Already from the early stage of PHEV applications development, the sudden engine cold start was raised as an upcoming challenge to be taken into consideration. The sudden transition from pure electrical to ICE propulsion, due to extra power request or low battery charge status, is very typical for PHEVs.

In general, the powertrain layout of the PHEVs has changed over the past years, from mainly high-end vehicles with high performance, to more common vehicles with extended electrical drive range. Nevertheless, the so-called high power cold start is always a critical use-case [1, 5, 7], even if probably less frequent on later PHEVs generation due to more mature and sophisticated technologies combined with the balance towards customer expectations.

Typically, emission test cycles like FTP75 or WLTC, in contradiction to sudden ICE start with torque demand, consists of an idle phase at the beginning of the test. During this idle period usually, the engine is calibrated with significant ignition retardation combined with high idle speed and a slightly lean lambda. This combination has been proven to allow optimal condition for low engine out emissions, steep temperature ramp for early light off and sufficient oxygen for exothermic reactions in the catalyst.

In the upcoming US legislation, the idle period for FTP75 is reduced from 20 seconds to 8 seconds. For PHEVs, where there could be no pre warning at all for an ICE start, US authorities now have updated the test procedure and included the US06 with cold engine start.

3.2 The Electrically Heated Catalyst

A typical electrical heated catalyst consists of a relatively short heating disk connected nearby to a more standard type of catalyst substrate (Figure 2). The electrical power that is typical for those disks is in the range of 4-6 kW on 48V applications.

This available power, that is converted in available heat, must be transferred as quickly as possible to a large volume of the catalyst, to cope with the PHEV high-power cold start challenge. Even better would be to have a large volume of preheated catalyst before this sudden ICE start.

An extensively discussed challenge is of course to know when pre-heating should be started since the vehicle can´t predict exactly the future torque request. It has been discussed the use of predictive software using on board cameras and maps connected with GPS. This very interesting topic will not be discussed further in this paper, and the investigation will be carried out under the assumption that the ICE start can´t be predicted.

The requested high electrical power to bring a big catalyst volume above the light off temperature is a challenge for the heating disk, both from a durability point of view, considering the high temperature changes, but also from a heating transfer point of view. This second aspect is strictly related to the uniformity of the flow in front of the disk itself. This is even more challenging when considering the tight space available for the installation of the EHC in front of the catalyst and the potential need of an auxiliary air introduction (AAI) to pre-heat the catalyst itself. The auxiliary air introduction has a positive effect on tailpipe emissions, as discussed in [11]. Possible positions of AAI are the exhaust manifold tubes in front of the turbo charger and the inlet cone in front of the catalyst. The optimization of the flow, coming from the turbocharger, with open and close wastegate, and coming from the nozzle, is a challenge and sometimes it is necessary to accept compromise flow distribution from the engine or from the nozzle due to space constraint.

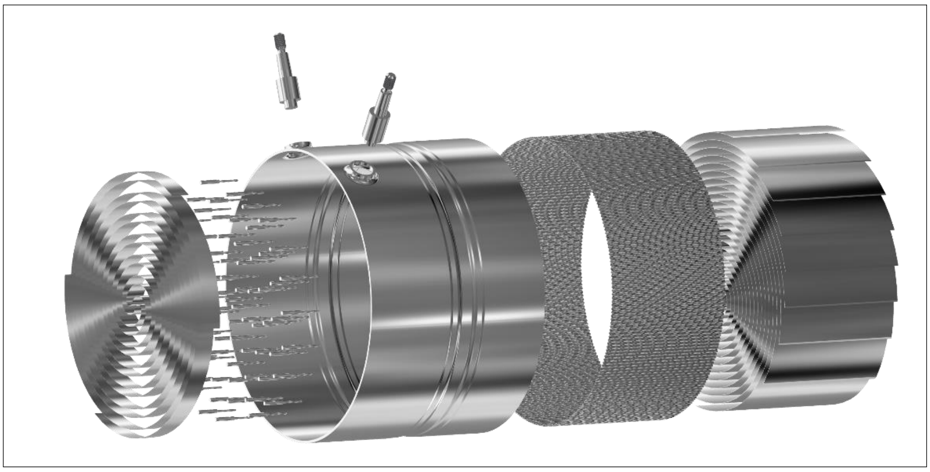


Fig. 2. Electrically Heated Catalyst

3.3 Catalyst Installation and EHC Installation

The company Aurobay, formed in the year 2021, is having design responsibility for catalytic converters in Volvo vehicles.

The most common of Volvo gasoline PHEV applications, introduced 2016 [9], had a catalyst system developed in collaboration with Emitec. The development of the so-called Compact Catalyst® is explained in [8] and also how this catalyst concept within the collaboration (Figure 3) ended into a patented solution as a two-brick system. It also explains the unique feature with the possibility to package a large catalyst volume in a small space in close coupled position. The innovation hereby could contribute to challenging battery installations. The installation is in this paper further on named as Generation 2 (G2).

Fig. 3. A common Volvo PHEV Exhaust System, in this paper named Generation 2 (G2)

Today, the most common versions of engines from Aurobay, have a high turbo installation. They belong to Generation 3 (G3) engine family [10]. Until today those engines are mounted in mild hybrid vehicles. The design is enabling space for catalyst installation in a different way. The design is scalable and also enables large substrate diameters supporting decreased back pressure. It is optimized for the best overall compromise for current applications and the flow distribution is optimized for catalyst function over normal operation. The turbo design, the inlet cone and the first substrate design are therefore tuned together. The catalyst design is shown in Figure 4.

In the flow distribution investigation described in this paper the electrical heated catalyst with auxiliary air is positioned at the same position as the front face of the standard substrate on G3. In chapter 5 the challenge of uniform flow distribution with AAI installed in a close coupled position on the G3 design, will be discussed. So far, this G3 layout with AAI is not validated for emission tests. Instead, for the emission investigation, to show the potential of the EHC and AAI, the tests were done with another layout which (Figure 5) was not aimed for PHEV though. The relatively long inlet cone and the straight part of it allow for an optimal auxiliary air introduction with a simple nozzle geometry.

Fig. 4. Generation 3 (G3) Volvo Exhaust System

3.4 The Electrically Heated Disk

In previous papers [1, 7] it has been discussed that the most beneficial position of the heater element is in the center of the catalyst, even if there are applications with the heater element in front of the first brick. One reason for that, was that the heating disk was coated and by having it beyond a first brick, the coating is protected from poisoning and ageing. The alternative, to have an uncoated heater disk is investigated in this paper and in this particular case, the aging of the heating disk is not an issue at all.

The Electrical Heated Catalyst (EHC) is a well-known and field-proven component and has already been in serial production in vehicle applications. The Electrically Heated Disk (EHD) is a new product, based on the same field proven components as the EHC and is by definition not coated, see Figure 6. According to extensive voice-of-customer interviews, a new stand-alone heater was developed to allow flexible installation at different locations in the exhaust aftertreatment system. To achieve this, the support catalyst matrix was removed, and replaced with a stainless-steel frame at gas inlet side, also called the support structure. All other key components were carried over from the EHC to design a robust heater while keeping the number of new components to an absolute minimum [11].

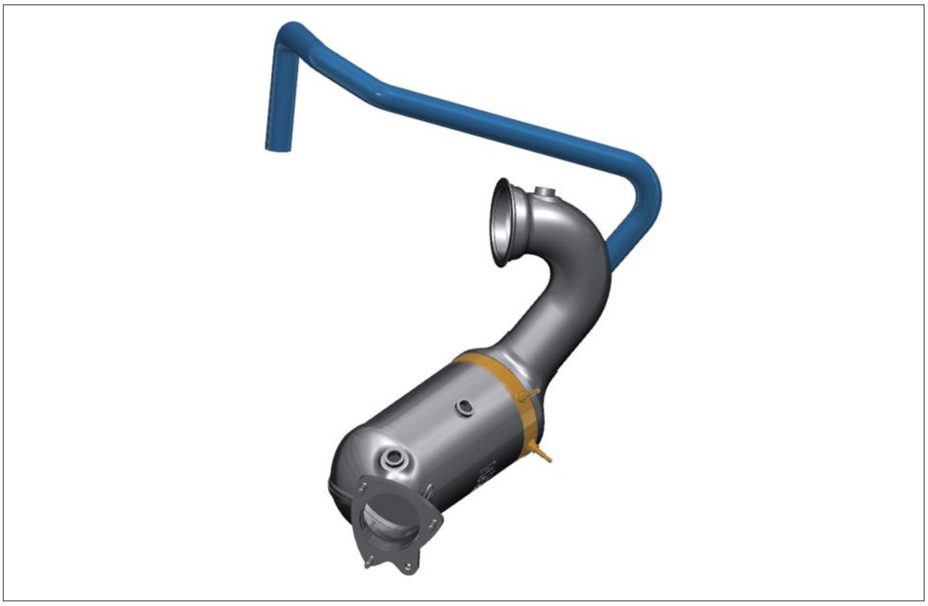


Fig. 5. System (including AAI inlet) used for Emission test

In the flow distribution investigation described in this paper the electrical heated catalyst with auxiliary air is positioned at the same position as the front face of the standard substrate on G3. In chapter 5 the challenge of uniform flow distribution with AAI installed in a close coupled position on the G3 design, will be discussed.

An alternative version of this technology, that has also been marketed from another supplier [13], consists of a single electrical heating disk with a different support design. From an application point of view, both the catalyst ageing and the OBD2 of an electrical heated catalyst are often raised as particular challenges. The first OBD2 question normally discussed is how to judge that all the heat energy that is supplied to the EHD comes to an effective emission advantage. This question is the same for any EHC or EHD solution. However, the issue about efficiency degradation, both for the OBD limit thresholds as well as for emission full useful life performance, is somewhat less severe in the EHD case compared to a coated EHC, this considering that the EHD does not have any coating on top, that can degrade over time. It may simplify a potential industrialization project, since many activities during the verification process relies on rapid bench aged parts, which would need to include an EHC but not an EHD. Less complexity simply means more straightforward development process, which likely helps achieving high robustness in the final product. Another aspect that can be seen as an advantage of an uncoated EHD compared to a standard layout without any EHD, is that during transients or extreme high loads, which are most critical for catalyst ageing, the

EHD (with no electrical heating applied) will to some extend act as a temperature shield and protect the catalyst brick behind (Figure 7).

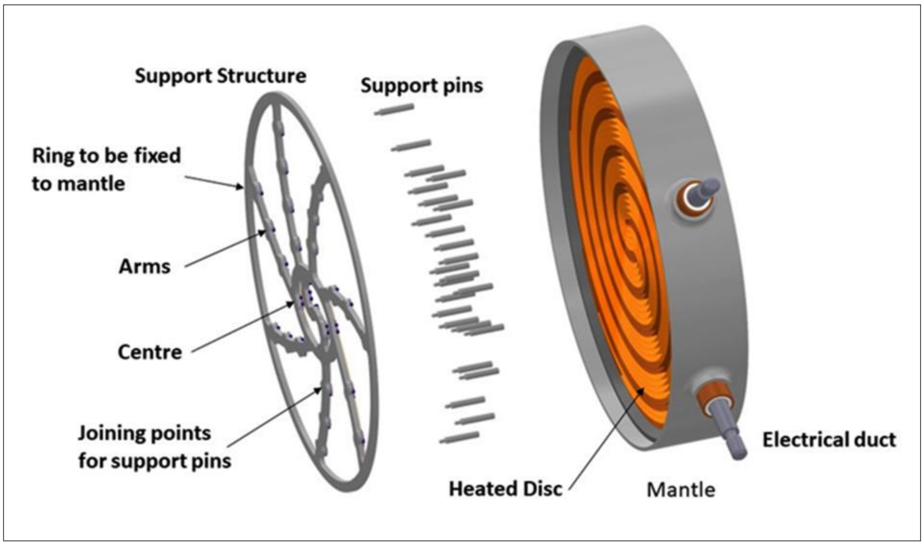


Fig. 6. Electrically Heated Disk

The effect can be understood since the (switched off) EHD reacts as a heatsink before the first coated substrate. Considering that the main goal of an EHD is to improve cold start, it is also a benefit for aging behavior of the first coated brick.

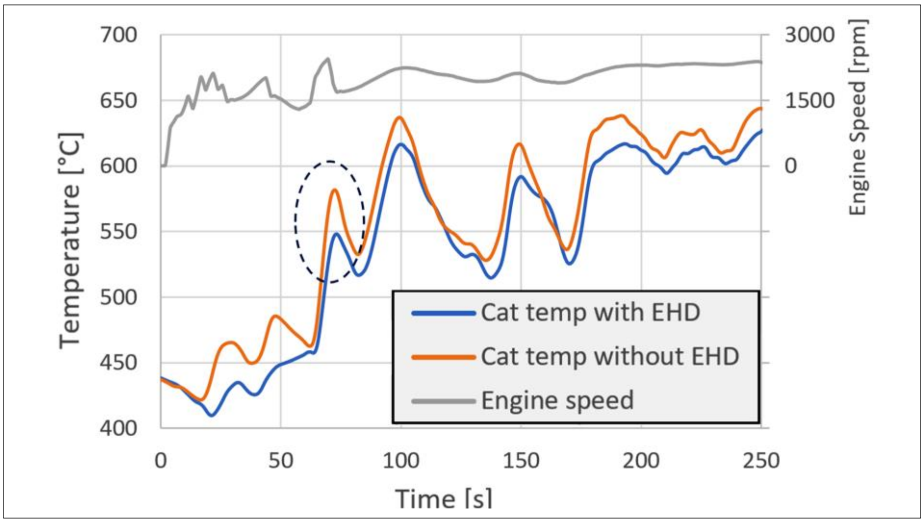


Fig. 7. As example dashed encircled shows 40°C lower temperature 8 mm from front face in first coated brick during one transient (Here a portion of WLTC cycle measurements)

3.5 Cost Efficiency and development of EHD system

The addition of an EHD to the catalyst system will increase costs. The potential here is to compensate these added costs, of the EHD itself, the cables and the controller, with a reduction in the catalyst PGM loading. It can be assumed that there is sufficient electric energy storage in the vehicle for any PHEV configuration.

Furthermore, from a system perspective, the desired emission performance together with overall complexity needs to be balanced. Previous system designs are gathered in Figure 8. In one study [1] system C was evaluated for cost and sustainability in a zero-emission impact context. Here a cost reduction is valid for the reduced PGM load. It can also be an attractive argument for contributing to the sustainability of ICE vehicles through improved air quality and lower mineral depletion of critical materials. Utilizing significantly less PGMs in the design, is an enabler for a higher portion of the PGMs from recycled catalysts. This low-cost catalytic substrate system had a 60% PGM reduction compared to a standard Eu6d system. It performed well, with over 90% cold start emission reduction compared with the Eu6d system. Compared with system D that was decided to test in this paper, system C had a second EHD. Furthermore, this system had its second substrate positioned under-floor. Both systems C and D utilize the same low cost TWC substrates.

The extra feature for system C, besides the extra heat from the second EHD, is the ability to convert condensed emissions. Hydrocarbons are solvable in water and when hot exhaust gas contacts the cold exhaust system walls, the water in the exhaust gas condenses, leading to the condensing of pollutants to the pipe walls for a period of time until the water later evaporates when those surfaces are heated. With system C, cold start emissions that slips through the front part of the system have an extra chance to be converted in the second part of the system, following evaporation from the cold walls inside the exhaust line. The experience and knowledge on how to utilize this effect was inherited from system B. System B was designed to reach a zero-emission impact target and evaluated [12] with less priority on cost and sustainability than system C. Other specification differences included a HC adsorber that was mounted in-front of the second electrical heater.

Experience has shown that it is possible to take advantage of emission condensation without a HC adsorber material when a heater and a catalyst are placed behind cold surfaces. An extreme version that utilizes this feature is exemplified in system E [14, 15]. It has until now only been tested with the condense-adsorber-device part, not having the heater as well, relying on that the hot exhaust gases manage to heat the catalyst enough before the condensed cold start emissions evaporate from the condense-adsorber-device. Combining geometries with heaters and cold surfaces can be an efficient approach to control and achieve extremely low emissions levels. Here pre-heating plays an essential part.

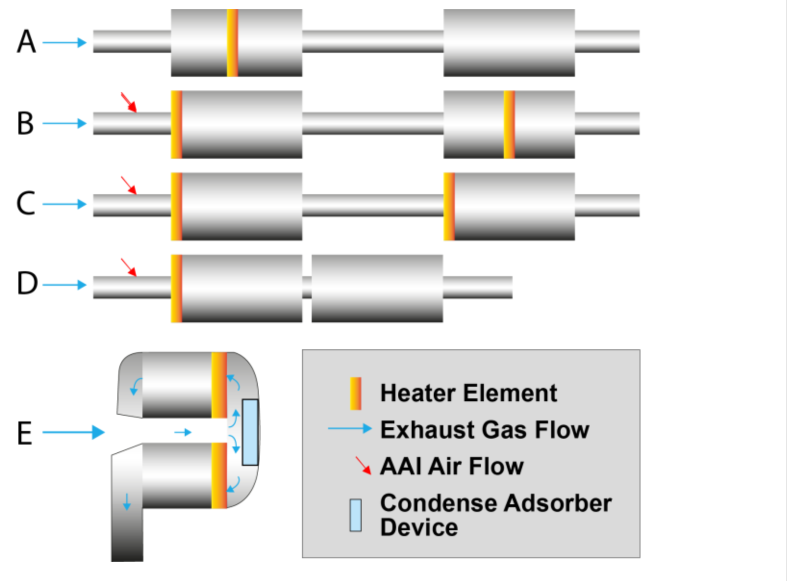


Fig. 8. Schematic representation of considered system design alternatives

Therefore, the system A [7] represents a good compromise also without AAI. When the heater in this case was embedded between two bricks, due to the insulation of the adjacent substrates, a large portion of the front catalyst avoids the delay of catalyst heating due to the already overcome dew point in the substrate. For a PHEV with it's typical packaging restrictions, as mentioned before, it was decided to aim for system D, judged as to be the best balance. Thereby also taking advantage of the ease to industrialization discussed in chapter 3.4. Combined with pre-heating and AAI, this system maximizes early conversion of gaseous and condensed cold start emissions.

3.6 Test Set Up Description

Typically EATS hardware evaluations are done on engine test bench or on complete vehicle in an emission test cell. A PHEV vehicle is more complicated than a standard ICE or MHEV vehicle with its dual propelling force sources (ICE and electric motor). It is a continuous interaction between the ICE power source and the electrical power source. The driver behavior and the state of charge of the battery are factors that effects the power demanded from the ICE. This becomes a source of spread in the evaluation of results from PHEV vehicles. It is then clear that especially a PHEV hardware investigation will benefit from being performed in a successful engine test cell setup.

Several variants how to reproduce tests from vehicle to rig have been judged. Aurobay have concluded to apply a method based on an add on for open loop torque control via CAN. A special engine management software that controls engine output torque according to a recorded trace is needed, with as few as possible interim steps that could alter the controlled torque output of the engine. With this approach, Aurobay have been able to replicate an almost 100% exact behavior of load, speed, ignition, fuel cut events and lambda as in the test from the car where it was recorded. One of the most important aspects of this method is that the variation test-2-test (often called repeatability performance) is excellent. Another thing that is important, is that this methodology allows to keep the original software calibration in the ECU. Otherwise, there is often quite some work to recalibrate, and by that it is not known if the test results are representative or not in the end. In addition to the above-mentioned advantages, the engine initial rev-up from stand still from the vehicle application, can easily be replicated thanks to original calibration designed with ISG starts.

Alternative test cell control options of the test cell as open loop or closed loop control of the throttle (or pedal) does e.g., not give representative behavior of fuel cut events. Attempts with a driver model and simulated gearbox and vehicle have not been even close to as representative with a reasonable work effort.

In this study one further step was investigated: the possibility to use an updated and newly developed engine than the one used in the test-vehicle. In the car, a G2 engine is used (G2 and G3 explained in chapter 3.3), while in this study, a G3 engine has been tested. But without having a PHEV vehicle already equipped with a G3 engine, no vehicle test was possible to perform. Therefore, the open loop torque control via CAN was the perfect way for this investigation, as it solves the interest in investigating how a desired EATS would behave in circumstances with a later developed engine.

To allow for several tests per day, a fast-cooling system for both the engine as well as for the exhaust aftertreatment was installed. It was also decided to reduce the test duration to only cover the most interesting parts. For the standard WLTC, the beginning and a total of 390 seconds portion was suitable, as there is a natural start/stop event at 390s in the WLTC cycle (Figure 9). The shortened cycle and quick cooling time allowed for a reduction in test time, resulting in the possibility to perform up to 8 tests per day in the engine test bed.

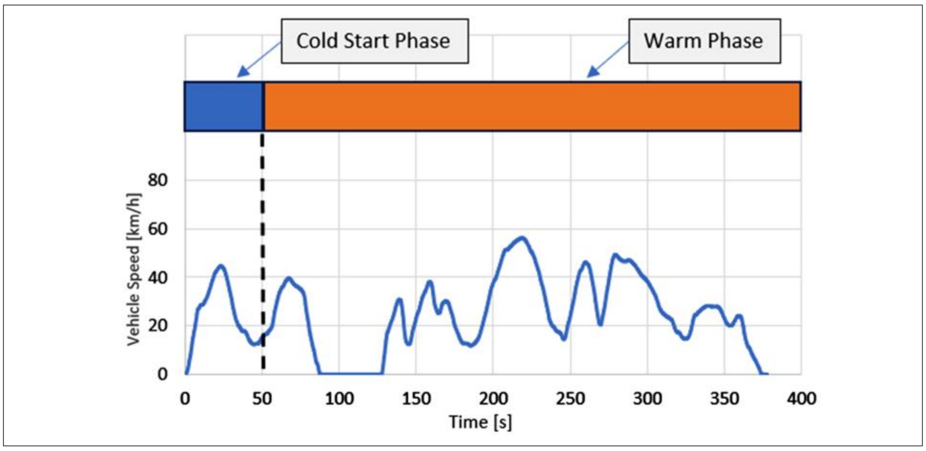


Fig. 9. WLTC Emission Cycle: Cold Start and Warm Emission Portion

For HPCS, the two most representative cycles regarding challenging sudden ICE starts were selected from the 10 cycles measured on the PHEV vehicle mentioned earlier. These were then used for the engine bench emission tests, reducing the test campaign complexity. These two cycles are named HPCS-A and HPCS-B and were also chosen with the respect of fitting in within the same duration and boundaries to keep the same test efficiency heritage as with the WLTC testing. Emissions were evaluated after 50 seconds to represent the cold start and take-off emissions. The results are explained in chapter 4.

Emission calculations are the same as those from vehicle emission testlab (VETSONE), however a CVS-tunnel is not used in the engine test cell, instead calculated total exhaust flow from the ECU is used.

3.7 Lambda offset during cold start

Tail Pipe emission measurement repeatability is of course very important for evaluation of catalyst systems. It is well known that the 3-way catalyst, by switching between rich and lean value, can reach a conversion efficiency in warm conditions above 99.5%. A typical production calibration is to start the lambda control as early as possible. However, even though this is the best choice for the individual application in production, it may not be the best option during catalyst hardware evaluation.

During the screening of different technologies and installations it is not possible to manage a full calibration development for each technology or installation. In this case, if the calibration is fully developed to the optimal for each solution, to do a fair comparison, more tests and further calibration work would be needed.

In our test campaign we decided to solve this issue by applying a special calibration strategy. This allows for a fair comparison of the different technologies, but with the drawback that NO_X emissions cannot be evaluated. We believe on the other hand, that it is sufficient to evaluate HC and CO in a first step and then we know by experience that we later can fully develop the control strategy to also optimize the conversion of NO_X.

The traditional calibration strategy during cold start is to start at lean lambda, then after some seconds perform a rich catalyst neutralization step. From this point on, in case of the production calibration, the lambda control would switch between the two target lambda values. But for this test campaign, a steady target lambda value was set to 1.02 (Figure 10), by using a special ECU software. Hereby, of course, there will soon be a poor NO_X conversion of the system.

One other positive aspect of this method is that the catalyst neutralization step after the lean cold start, is carried out as is typical done in final production applications. This helps to keep the catalyst coating material in a state that is as normal as it is possible, with the special (lean) lambda control approach. As comparison, a completely lean start combined with a lean take off, without the rich neutralization step, is judged to be less representative for how precious metals and oxygen storage are treated in a standard calibration.

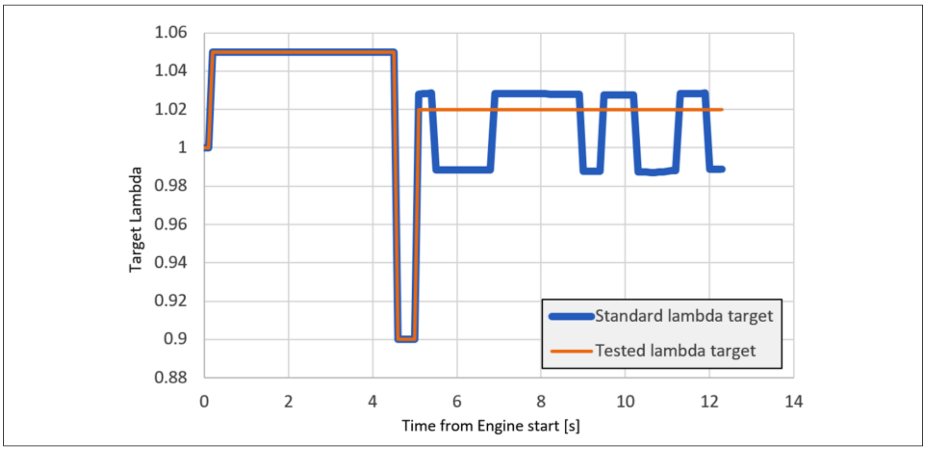


Fig. 10. Target Lambda Value: Standard and Test Approach

4 Emission Test with the Aurobay Zero Emission Engine

4.1 Comparing catalyst challenge WLTC vs HPCS

The High-Power Cold Start cycle is challenging and somewhat unique. There is an instant high load and high engine speed increase during a short phase just after engine start, which is highly challenging for emissions control. This is directly followed by a moderate load phase since the E-drive takes over the propulsion of the vehicle as soon as it is able or allowed to do so. In this phase the ICE is mainly charging the battery. This type of PHEV start means, in our assumption, a very instant need of active catalyst volume for conversion.

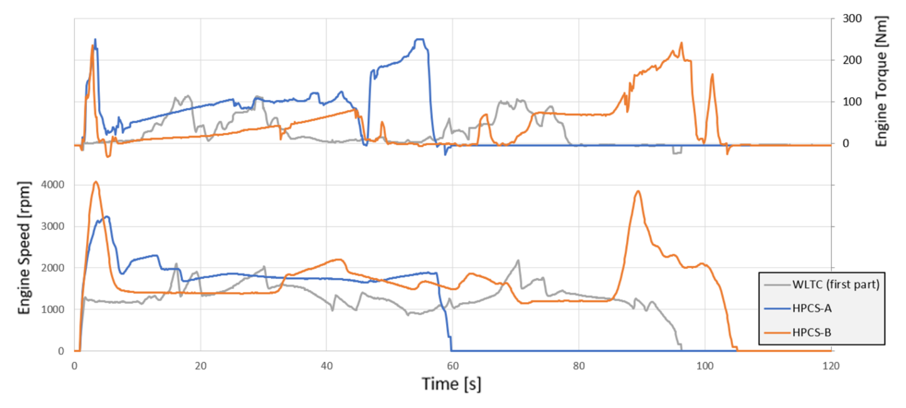


Fig. 11. Torque and Engine Speed Traces during the Test Cycles (first 120 seconds)

The test cycles were performed by applying the described approach, using the trace replication method, in conjunction with the special lambda control strategy, described in earlier chapters. A comparison of the cycles, the torque and the engine speed, are shown in Figure 11. The picture shows the two PHEV cycles: HPCS-A and HPCS-B, in relation to the beginning of a mild hybrid (MHEV) WLTC cycle.

For a more detailed comparison, a zoom in on a few other signals during the first 30 seconds, explains the preconditions for the catalyst light-off challenge, see Figure 12.

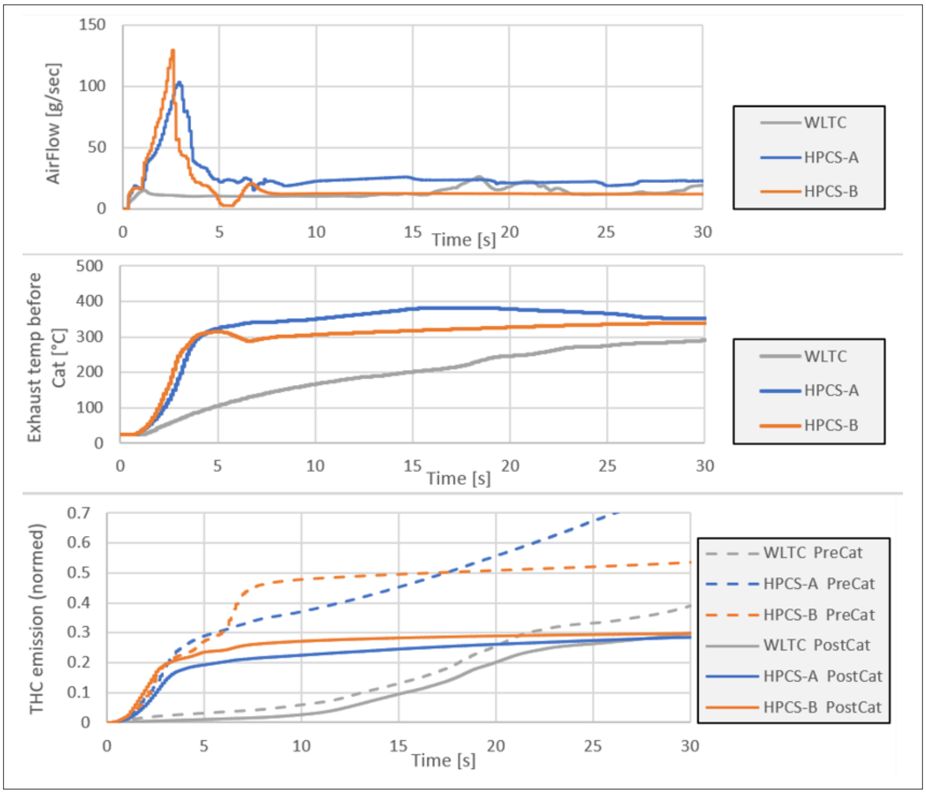


Fig. 12. THC emissions, catalyst inlet temperature and engine inlet air mass flow during the first 30 seconds

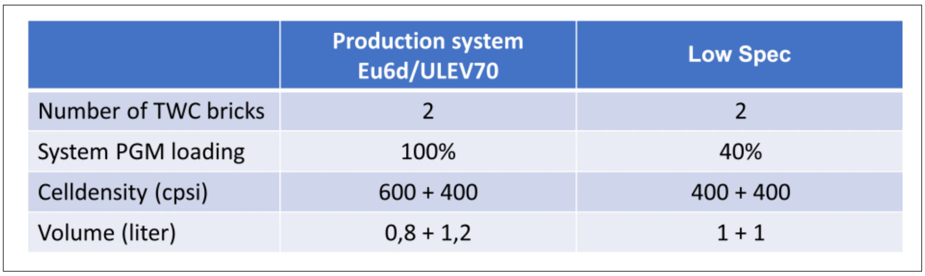
It can be seen in Figure 12, how both HPCS versions bring a significantly increased catalyst challenge regarding the cold start emissions compared with the WLTC on a mild hybrid. The THC engine out emission and air mass flow peaks just after engine start, confirms this. An observation here is also that the accumulated THC tailpipe emissions from both HPCS cycles, reaches a similar level to the WLTC cycle after around 30s seconds for this catalyst system setup. By that even with higher engine out emissions, some compensation is achieved when the catalyst light-off occurs considerably earlier due to the increased energy flow from the instant high-power output of the ICE. In addition, it should be noted that the total emissions from a PHEV during harsh driving compared to a standard mild hybrid with a WLTC cold start, are comparable.

The HPCS-A and the HPCS-B cycles are quite different to each other. The HPCS-A cycle has in comparison, a relatively high load after the start period. On the other hand, the HPCS-B has a much more aggressive start. Compared with a mild hybrid during harsh driving (example US06), the mass flow typically stays lower in the PHEV use-cases. Those are interesting observations to keep in mind for catalyst design discussions.

4.2 Emission Test results with and without Auxiliary Air

Even though emissions are not severe from HPCS, in comparison to WLTC as discussed in previous chapter, it is of course interesting to compare what the system design uniqueness means for PHEV’s. This since possibilities for newer stricter legislations can be needed to consider. For the test campaign discussed here, only WLTC and HPCS at ambient temperature, +23° C, has been investigated. The aftertreatment system has a high degree of added complexity when it comes to mechatronics. One EHD together with an auxiliary air system brings a high degree of freedom for parameter settings and in turn, automation application work. In this case, the electrical power of the EHD and the air mass controller for the auxiliary air, were both controlled directly from the test cell. The EHD power unit offered full flexibility of voltage and current for a power range up to 10kW.

The base catalyst system chosen is named LOW SPEC in table 1 and is compared with one of the currently most common production variants designed for EU6d and ULEV70 regulations. The LOW SPEC system was designed with the target to reach a 70% decrease in PGM mass compared to today’s standard EU6d vehicle. This PGM target relates to the fact that 30% of the used PGM today in production for new vehicles are being recycled. Furthermore, it was also desired to compensate the increased cost of the EHD system at least partly. To achieve a low-PGM system it was critical to minimize the catalyst specification as much as it was practically possible. A total catalyst volume of 2 liters was chosen (Table 1). From available parts, we decided to stay at 60% decrease of PGM.



	Production system Eu6d/ULEV70	Low Spec
Number of TWC bricks	2	2
System PGM loading	100%	40%
Celldensity (cpsi)	600 + 400	400 + 400
Volume (liter)	0,8 + 1,2	1 + 1

Table 1. Properties of the tested catalyst system (production system for comparison)

Three different heating strategies with EHD have been investigated (Figure 13). One of the heating strategies combines pre-heating and AAI.

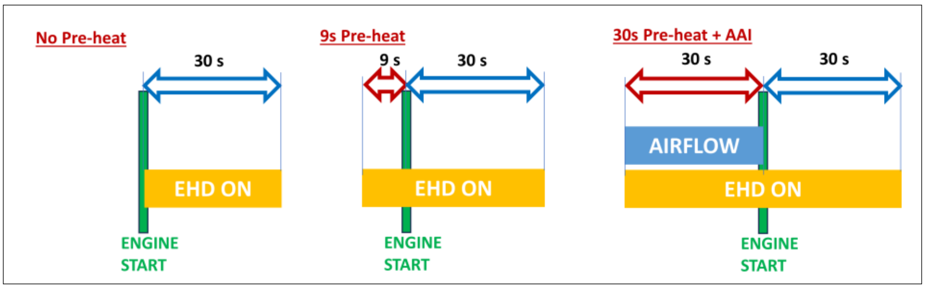
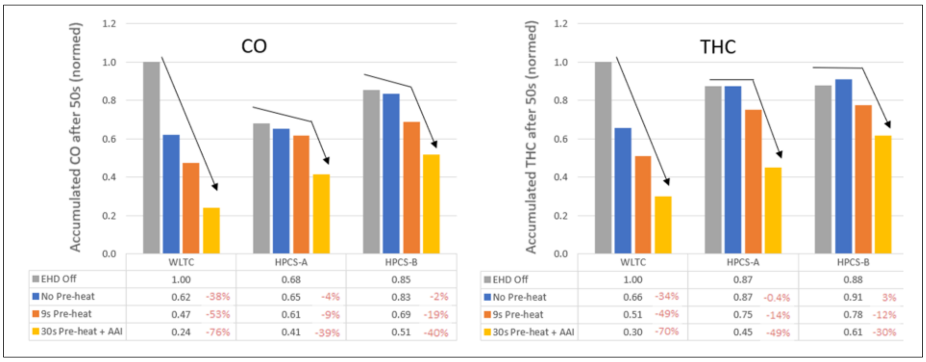


Fig. 13. Tested Heating Strategies

For the reference without heating, the EHD was taken out from the catalyst system, otherwise it would have acted as an unrealistic heat sink, that would have deteriorated the reference emission level in a non-representative way. All tests with EHD heating, used a post-engine-start heating period of 30s with 4kW EHD power. Pre-heating without AAI had a duration of 9 seconds and pre-heating with AAI had 30 seconds duration, in this case the heating power was 5 kW with an air mass flow rate of 30 kg/h.



	WLTC		HPCS-A		HPCS-B	
■ EHD Off	1.00		0.68		0.85	
■ No Pre-heat	0.62	-38%	0.65	-4%	0.83	-2%
■ 9s Pre-heat	0.47	-53%	0.61	-9%	0.69	-19%
■ 30s Pre-heat + AAI	0.24	-76%	0.41	-39%	0.51	-40%

	WLTC		HPCS-A		HPCS-B	
■ EHD Off	1.00		0.87		0.88	
■ No Pre-heat	0.66	-34%	0.87	-0.4%	0.91	3%
■ 9s Pre-heat	0.51	-49%	0.75	-14%	0.78	-12%
■ 30s Pre-heat + AAI	0.30	-70%	0.45	-49%	0.61	-30%

Fig. 14. Emission Results

All results in Figure 14 are the averages of 3 tests with near negligible individual variation. The difference between the strategies is to some extent dramatic. The WLTC results can benefit significantly already from the mildest version of EHD strategy without any pre-heating nor AAI. The HPCS versions needs at least some pre-heating, but it is only with the AAI strategy, that the emission reduction is significant.

The 9s preheating case shows approximately 50% benefit for WLTC, whereas 20% for the HPCS cycles, which can be judged as only a moderate improvement. Lastly the pre-heating with AAI has almost 80% benefit for the WLTC and in this case we also see a strong benefit on the HPCS cycles with a 40-60% improvement. It can be stated, considering the overall performances of the three heating strategies, that only EHD Pre- and Post-heating is not as effective in HPCS cycles as it is in the WLTC cycle. AAI has a great beneficial effect in the HPCS cycles. So, one could argue that PHEV need to consider AAI if considering an electrical heater solution. Then this of course depends on the overall system specification, together with the level of drivability quality that the final product aims for. It is mentioned earlier that the WLTC looks really promising with the simplest heating strategy. A PHEV have a big potential, especially in the case when the customer attributes like drivability and customer convenience is sacrificed. Then a cold start is more balanced towards emissions and will thereby avoid the unique challenges from a HPCS, that is described in this chapter.

5 Optimization of Auxiliary Air Nozzle Position for G3 catalyst geometry

The auxiliary air injection in the inlet cone has been investigated in a previous work [6] where it has been demonstrated how a uniform velocity distribution is a key factor to have an efficient heat transfer for the heating device to the catalyst. A uniform velocity distribution maximizes the heat transfer from the disk to the air or the exhaust gas, avoiding the presence of hot spot, that could limit the maximum power applied to the EHD/EHC itself.

The focus of previous investigation was on the influence of the velocity distribution on the pre-heating performances, without paying too much attention to the design of the nozzle or the possible use of the nozzle design for serial production.

These tests have been carried out using an available EHC. No differences in flow distribution and velocity distribution are expected according to the same layout of the disk on the EHC and EHD.

5.1 Comparing catalyst challenge WLTC vs HPCS

In an early test campaign, the auxiliary air introduction point was positioned in front of the turbocharger. In this case, the waste-gate was kept close. The flow distribution measurements have been carried out at room temperature with a mass flow rate of 10 and 30 kg/h. Both are representative of mass flow rate with market available air pumps.

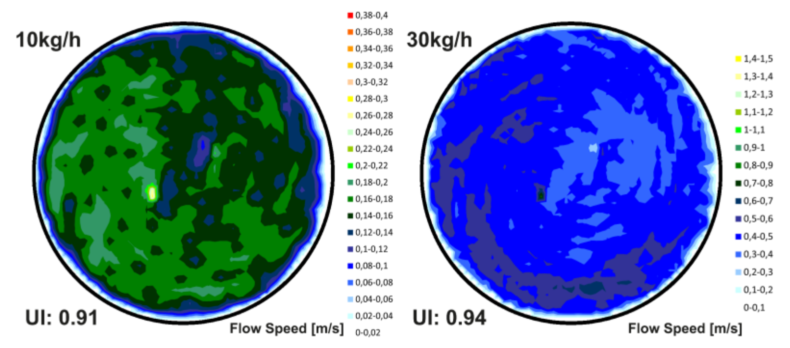


Fig. 15. Flow Distribution with AAI in front of the turbocharger (please take into consideration the different velocity scale)

While the uniformity index is a commonly used parameter to judge how good is the flow distribution on a surface, the velocity distribution (Figure 16) is used here to better explain how fast the heat generated on the EHC / EHD heated surface can be transferred to the air and then to the catalyst.

If the distribution of velocity is concentrated around the mean value, it means that in a very large part of the surface the flow velocity will be the same or similar to the mean value, increasing in this way the heat exchange area between the hot EHC / EHD surface and the cold auxiliary air flow.

On the other hand, if the shape of the flow velocity distribution is "flat", it means that on the surface there will be areas with higher velocity, where the heat exchange is good, but also areas where the flow is slower, and the heat exchange is worse. This is a situation that must be avoided, to prevent overheating areas.

Both uniformity indexes (Figure 15) and velocity distribution (Figure 16) are quite good, in this case.

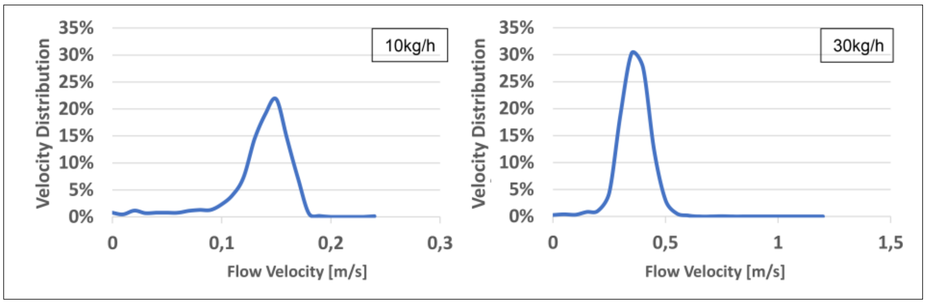


Fig. 16. Velocity Distribution with AAI in front of the turbocharger

In this test campaign, the goal was to check how long it was possible to heat up with 4 kW before reaching the max temperature (900°C) in the hot spot. With 10 kg/h it was possible to heat up 30 seconds, while with 30 kg/h it was possible to heat up 90 seconds.

In the next step the position of the AAI was moved to the inlet cone, considered that this could be a more viable solution for a serial production. It was also decided to keep the heating time within 30 seconds.

5.2 Test with AAI in the Inlet Cone

For the present investigation, a potential intended serial production nozzle design has been used. In order to carry out flow distribution measurements with the nozzle in different positions, the inlet cone and the nozzle itself have been 3D-printed. This allows for a quick modification of the nozzle position and inclination, as shown in Figure 17.

Fig. 17. 3D-printed Nozzle and G3 Inlet Cone, connected to the turbo charger, baseline 0° (left) and 120° (right) Nozzle Position

Measurements were also done with a mass flow of 10 and 30kg/h at room temperature. The inlet cone has been connected with the turbo charger to replicate the flow conditions of the real application.

The flow distribution is measured using a hot wire with a mesh resolution of 5 mm, shown in Figure 18 as a schematic illustration.

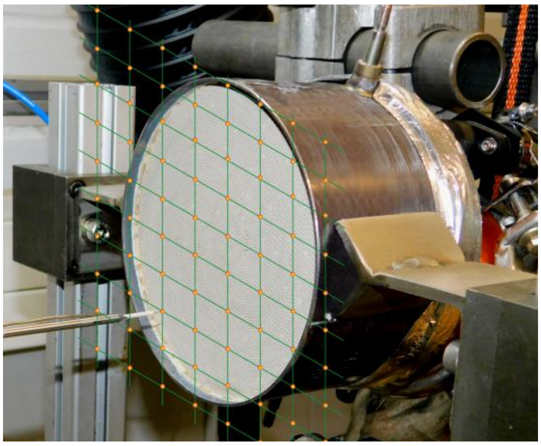


Fig. 18. Test Set-up for the uniformity index flow distribution

To assess the effect of the flow distribution on the heating performance of the EHC, a set of infra-red measurements have been carried out.

5.3 Flow and Temperature Distribution with 10 kg/h mass flow rate

The first tests have been carried out with a mass flow rate of 10 kg/h at room temperature (20°C).

Figure 19 show the influence of the nozzle position on the Uniformity Index (UI) and generally on the position of the high flow velocity area.

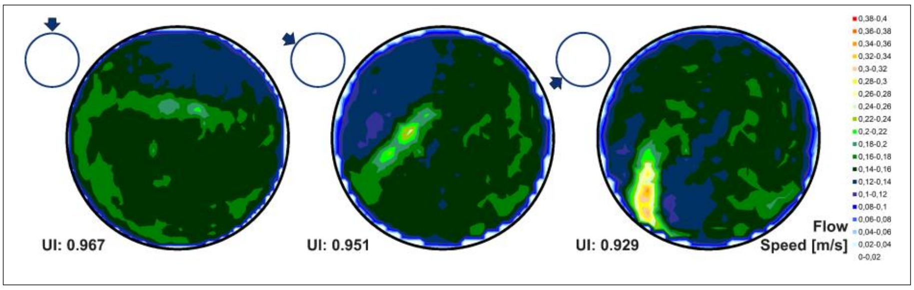


Fig. 19. Flow Distribution and Uniformity Index (UI) for the three tested nozzle positions

The flow velocity distribution, as reported previously, is a key parameter to better understand if the EHC/EHD can reach its maximum power with that particular flow field. The flow velocity in an empty tube under the given boundary conditions would be 0,146 m/s. The flow velocity distribution (Figure 20) of the layout 1 (with 0° nozzle position) is very promising, the flow velocity distribution curve is very narrow. Layout 2 (with 60° nozzle position) and layout 3 (with 120° nozzle position) have a lower percentage of the velocity flow at the theoretical value, this means that they have also more areas with very low flow, resulting in the heat exchange coefficient of the layout 2 and layout 3 to be lower than the one of layout 1.

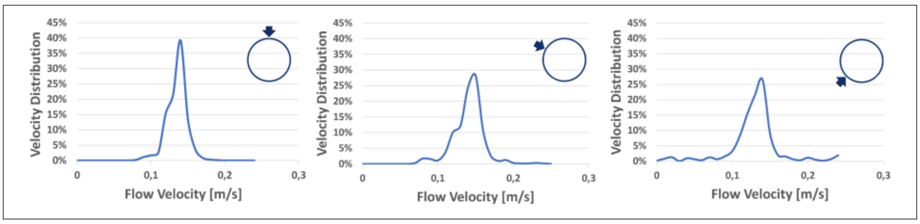


Fig. 20. Flow Velocity distribution for the three tested nozzle positions, 10kg/h mass flow rate

Layouts 1 and 3 have been chosen for the Infra-Red measurement. Layout 1 as the more promising and layout 3 as the less promising.

5.4 Infra-Red Measurement with 10 kg/h mass flow rate

The test has been carried out applying the maximum possible power for 30 seconds with the limit of the 900°C at the hot spot and 10 kg/h mass flow rate at room temperature.

Figure 21 shows the results of the Infra-red measurements: both configurations perform quite well. Layout 1 has a higher mean temperature, and 3.3 kW can be applied, while layout 3 has a lower mean temperature and 3.2 kW can be applied. The small advantage in maximum applied power and mean temperature of the layout 1 confirms the importance of a good AAI flow distribution even if it should be noted that the Hot

Spot is near the mantle, where all three configurations have similar flow conditions. A possible, further, optimization could be, to increase the flow conditions near the hot spot.

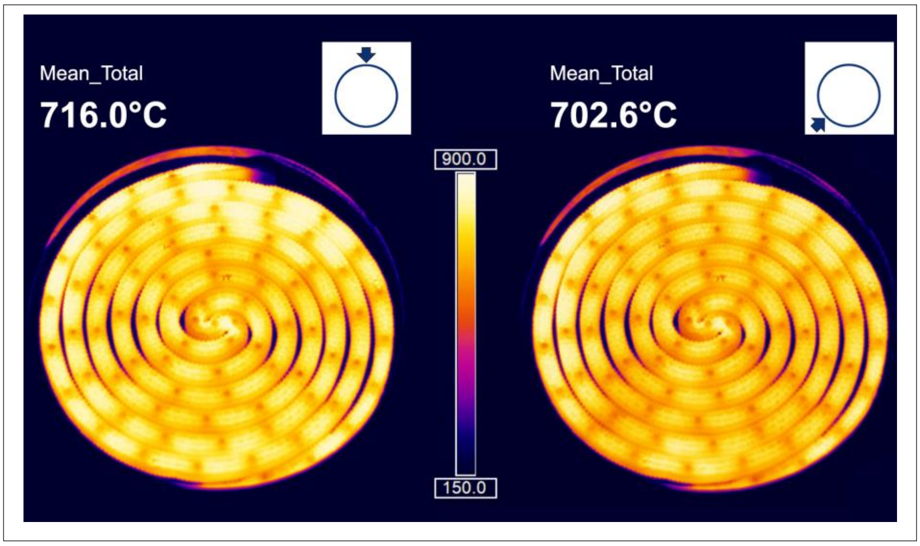


Fig. 21. Infra-Red Measurement of Layout 1 and 3, Max (Picture) and Mean Temperature after 30 seconds

5.5 Flow and Temperature Distribution with 30 kg/h mass flow rate

The second set of tests has been carried out with a mass flow rate of 30 kg/h at room temperature (20°C).

Figure 22 shows the influence of the nozzle position on the Uniformity Index (UI) and generally on the position of the high flow velocity area.

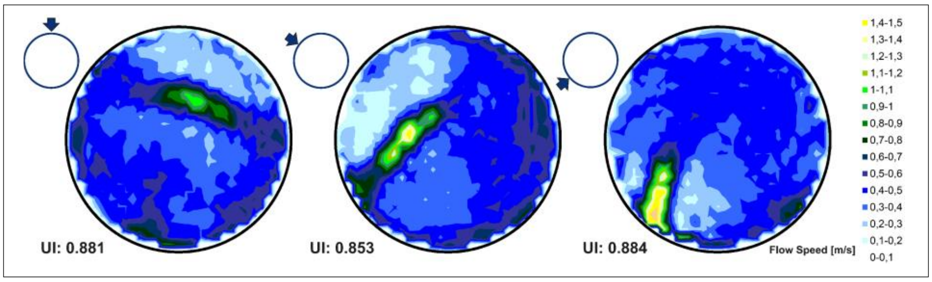


Fig. 22. Flow Distribution and Uniformity Index (UI) for the three tested nozzle positions

Figure 23 shows the flow distribution of the three tested nozzle positions.

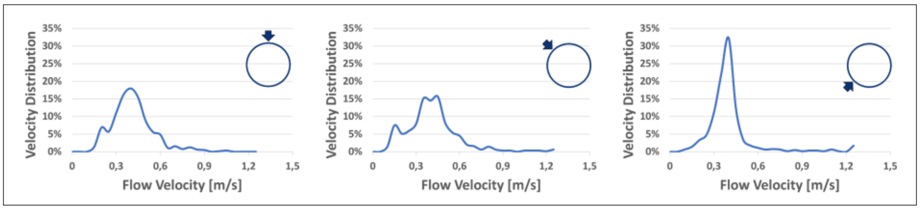


Fig. 23. Flow Velocity distribution for the three tested nozzle positions, 30kg/h mass flow rate

Comparing the velocity distribution, it is quite evident that the layout 3 has the highest potential, even if the flow distribution of layout number 1 could be also promising.

For the infra-red measurement, the layout 1 and the layout 3 have been chosen.

5.6 Infra-Red Measurement with 30 kg/h mass flow rate

The test has been carried out applying the maximum possible power for 30 seconds with the limit of the 900°C at the hot spot and 30 kg/h mass flow rate at room temperature.

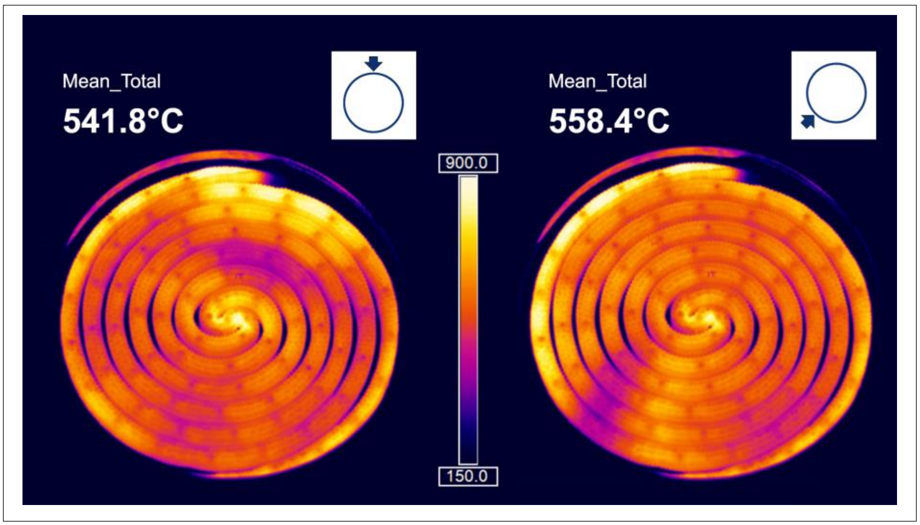


Fig. 24. Infra-Red Measurement of Layout 1 and 3, Max (Picture) and Mean Temperature after 30 seconds

Figure 24 shows the results of the Infra-red measurements, the cold area where the flow speed is higher are very well visible. The layout 1 reaches its maximum temperature after 30 seconds when 3.8 kW are applied, while it is possible to use 3.9 kW on the layout 3. The layout 3 has a slightly higher mean temperature. The same considerations as for the case with 10 kg/h on the position of the hot spot can be made also for this use-case: an improvement of the flow conditions near the hot spot could led to increased applied power, even if 3.9 kW can be seen as a very promising result.

5.7 Test results of AAI influence

With low mass flow rate, the flow distribution of the two nozzle positions (in front of the turbocharger and in the inlet come) are very good, but the applied power is higher with the nozzle in front of the turbocharger. This is due to the fact that that flow is well distributed around the hot spots, not only in the center of the EHD. With higher mass flow rate the position in front of the turbocharger shows a clear advantage, but a further optimization of the nozzle position in the inlet cone could improve the situation and allow even higher electrical power.

6 Discussions test results

In previous investigations [1, 12], the combination of AAI and EHC/EHD has proven to be capable to reach a close to zero emission impact level during WLTC. That was with EHC/EHD both in closed coupled and under floor position. In this investigation the system was more moderate equipped with a single EHD. This together with low specified substrates provides an overall compensated approach regarding cost.

It is expected, with continuously increasing market share of PHEV at least within ICE equipped portion of vehicles, that the test on WLTC will be not sufficient to judge the efficiency of an EATS during RDE. Moreover, PHEV have further unique use-cases and in the U.S. the HPCS will be soon introduced as part of the emission certification. Then there is a need to investigate those use-cases in early development. As predevelopment investigation we could apply the use-case from an existing PHEV into a newer engine by simulating the electric drive in the test bench with reliable vehicle correlation. In comparison to WLTC: a large catalyst volume during a very short time period, just after the internal combustion engine start, is instantly needed to prevent high tailpipe emission. The exact use-cases will of course depend on the final PHEV product. Still, early knowledge from the first assumption of upcoming application is of strong value.

The work done shows how the AAI in combination with EHD and pre-heating might be a key technology to achieve a near-zero tailpipe emission even with PHEV during HPCS.

AAI must be optimized to transfer the heat generated over the EHD to the catalyst, taking also into account that during the HPCS a large catalyst volume above the light off temperature is needed, and allow a high power to be applied on the EHD itself.

The authors have used an experimental methodology to measure the flow uniformity index and the flow velocity distribution in order to assess if a given nozzle position can be used in an EATS in combination with an EHD. The goal is to use, during pre-heating, as much as possible the available heating power, without having overheating areas, which can be dangerous for system durability.

7 Conclusion and outlook

It has been demonstrated how the combination of AAI and EHC / EHD, in particular for the PHEV use-cases, have the potential to balance customer attributes with system cost and legislation.

PHEVs have unique possibility to integrate preheating thanks to extended electric drive capability and thereby take advantage of AAI.

Nozzle optimization is crucial to take full advantage of EHC and EHD in this context. Development of an optimized nozzle would have a positive effect on cost, environment, and sustainability. In a next investigation, CFD model will be validated using the results of this test campaign and new positions of the nozzle will be investigated. A possible further development of the measurement could be the use of a glass window on the inlet cone to measure the temperature distribution of the EHC / EHD during preheating and auxiliary air introduction.

Selecting in particular an EHD solution (instead of EHC) may have many benefits regarding aging of the first coated brick and OBD2.

Alternative fuels that are non-fossil are also crucial for the future of ICE and therefore PHEVs. The eFuel mainstream is not yet defined, but at least some of todays (methanol, ethanol) fuel compositions can bring additional cold start challenges and the investigation of EATS with AAI and EHD can bring also a possible solution for these challenges.

References

1. How to Accomplish a More Sustainable Internal Combustion Engine Using Life Cycle Analysis: A Demo, Joshua Paul Dudley, Mats Laurell, Christoffer Thuve, Henrik Klövmark, Aurobay; SAE Energy & Propulsion Conference & Exhibition, Greenville, USA, 2023
2. Unlimited Clean Mobility Emission Management for EU 7 and China 7 Powertrain Concepts Rolf Brück; Ines Lienou L.; Dr. Axel Schatz, Vitesco Technologies Emitec GmbH; Lohmar, Germany; Dietmar Ellmer, Vitesco Technologies; Regensburg, Germany; Aachen Kolloquium, Germany, 2020
3. The Exhaust Aftertreatment for Future World-Wide Internal Combustion Engines; From Passenger Car to Trucks, Rolf Brück, Dr. Manuel Presti, Lorenzo Pace, Frank Bohne, Jan Hodgson, Jan Kramer, Emitec Technologies GmbH, Lohmar, Germany; Aachen Kolloquium, Germany 2023
4. Characterization of Gaseous Emissions from Blended Plug-In Hybrid Electric Vehicles during High-Power Cold-Starts, Allen Pham, Marko Jeftic, California Air Resource Board, SAE Technical Paper 2018-01-0418, 2018
5. Exhaust Aftertreatment Technologies for Hybrid Electrical Vehicles, Lorenzo Pace and Rolf Brueck, Vitesco Technologies Emitec; Paul Rodatz and Peter Senft, Vitesco Technologies; SAE ICE, Capri, Italy, 2021
6. Innovative Catalyst System to Achieve EU7 Legislation for Electrified Powertrains, Rolf Brück, Katrin Konieczny, Vitesco Technologies Emitec GmbH, Lohmar; International Vienna Motor Symposium, Wien, Austria, 2022

7. Strive for zero emissions impact from hybrids, Mats Laurell and Fredrik Ekström, Volvo Car Corporation, Katrin Konieczny and Lorenzo Pace, Continental Emitec; SAE ICE, Capri, Italy, 2019
8. The innovative exhaust gas aftertreatment system for the new Volvo 4 Cylinder Engines; a unit catalyst system for gasoline and diesel cars, Mats Laurell, Johan Sjörs, Staffan Ovesson, Mats Lundgren, Volvo Car Corporation, Rolf Brück, Manuel Presti, Emitec GmbH; Aachen Kolloquium, Germany, 2013
9. Fleiss, M., Thomas M. Müller, Martin Nilsson, Jonas Carlsson, “Volvo Powertrain Integration into Complete Vehicle”, ATZ 03/201
10. The New Aurobay 250 PS, 2.0 L Miller Engine, Michael Denny, Andreas Berntsson, Ayolt Helmantel, Aurobay, Gothenburg, Sweden; Aachen Kolloquium, Germany, 2023
11. The Exhaust Aftertreatment for Future World-Wide Internal Combustion Engines; From Passenger Car to Trucks, Rolf Brück, Manuel Presti, Lorenzo Pace, Frank Bohne, Jan Hodgson, Jan Kramer, Emitec Technologies GmbH; Aachen Kolloquium, Germany, 2023
12. The sustainable engine; towards a provider of power and torque with zero resulting environmental impact, throughout the complete life cycle, Tomas Johannesson, Joshia Dudley, Mats Laurell, Aurobay; Aachen Kolloquium, Germany, 2022
13. Technology options to reduce cold start – electric catalyst heaters, Florian Kunath, Dominik Rose, Bertrand Coulet, Per Nicolin, Thorsten Boger, Thomas A. Collins, James M. Grochocinski, Mrinmoy Dam, Corning; Aachen Kolloquium, Germany, 2022
14. US20170184001A1 Volvo Cars Patent: Catalytic Converter and Exhaust Gas Aftertreatment Arrangement Catalyst Substrate Innovation for Achieving RDE and SULEV 30 Emission Legislation, Rolf Brück, Peter Hirth, Bin Hu, Christian Schorn, Continental Emitec GmbH; International Vienna Motor Symposium, Wien, Austria, 2016