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1) Introduction

The continuing success of European diesel engines is due to the fact that they combine low actual fuel consumption with great driving pleasure. The excellent power delivery and high torque of modern diesel engines have been amply demonstrated under everyday driving conditions. To continue their long-term international success they will have to comply with all current and future emission limits. Further advances in engines and catalyst and filter technologies will have to be made to comply with strict particle (PM) and nitrogen oxide (NOx) limits, particularly in the US where legislation does not differentiate between petrol and diesel engines. This so-called fuel-neutral legislation is also being discussed in Europe so that emission limits similar to those in the US have to be expected in the long term. Since Europe has become somewhat of a pioneer leading many, especially Asian, countries in the field of exhaust gas legislation, it is very likely that similar emission limits will be adopted worldwide in future.

As a first step towards compliance with future emission limits combustion processes and engines will have to undergo further development. The first success stories already show how homogeneous charge compression ignition (HCCI) can reduce both engine particles and nitrogen oxide emissions [1,2]. Engine components such as variable valve control and exhaust gas recirculation systems will gain in importance.

The limits discussed in connection with new emission legislation, such as EURO4, EURO5, EPA07 and EPA10, in particular demand high exhaust gas cooler performance.

This paper deals primarily with the future significance and requirements of exhaust gas recirculation systems (EGR) and in this context especially with exhaust gas recirculation coolers.

2) Exhaust gas cooler requirements

The exhaust gas cooler significantly cools down the between 500 and 700°C hot exhaust gas and so reduces combustion chamber temperatures and with it NOx raw emissions from the engine. The considerable reductions in NOx levels required by emission legislation are accompanied by a corresponding increase in recirculated mass flows and decrease in the necessary exhaust gas temperatures. While Euro 3 required car exhaust gas temperatures over 200°C, the exhaust gas temperatures discussed for Euro 5 applications range from 110 to 140°C behind the exhaust gas cooler. This can only be achieved through the use of highly efficient exhaust gas coolers [3,4].

Recent publications discuss the application of different EGR systems, such as high-pressure or low-pressure EGR systems, or even a combination thereof [5]. In principle, an EGR system is an emission-relevant system because of its impact on raw emissions and therefore has to be monitored as part of onboard diagnostics. However, as a result, every component of an EGR system must remain stable over the entire life of the vehicle.

New generation exhaust gas coolers have to withstand enormous operational demands. The highly transient processes in diesel engines expose the exhaust gas cooler to high pressure surges. In addition, the cooler is subject to a high thermal load when the exhaust gas recirculation valve is opened. Apart from stability, cooling capacity is the most important factor for modern exhaust gas coolers since this, as mentioned above, affects the level of NOx emissions from the engine. The thermal capacity of an exhaust gas cooler is largely determined by the design, the heat exchange surfaces and the heat transfer in the cooler [6]. During driving cycles the cooling capacity may be reduced because of soot precipitation, which affects the thermal transfer from the gaseous phase through the cooler wall to the cooling medium. There is a simultaneous increase in pressure loss, which means that the necessary recirculation rates can only be achieved by further opening the exhaust gas recirculation valve. Once the exhaust gas recirculation valve is fully open any further pressure loss in the cooler will lead to a reduction of the exhaust gas mass flow. Apart from the chemical elements in the exhaust gas, the other important factor in this context is the specific design of the exhaust gas cooler.

Behr GmbH & Co. KG has been working on the development of so-called winglet tubes for the past ten years [3]. These tubes permit a high degree of heat exchange and limit the precipitation behaviour of soot particles. The vortices generated by the winglet structure and the resulting turbulence near the walls also play a major role in this.

Figure 1*: Exhaust gas cooler block with winglet tubes and one half of a winglet tube*

Compared to smooth or twisted tubes winglet tubes are much less susceptible to fouling. For example, soot precipitation on the structure of twisted tubes leads to the loss of twist.

The great advantage of winglet tubes is that soot precipitation has only a minor effect on the generation of vortices since the deposits do not cover the winglets completely [3].

The mechanism leading to the accumulation of wall deposits can be described as follows:

- Condensation of hydrocarbons on the “cold” wall of the cooler
- Ash and soot particle precipitation caused by impact (gas flow, turbulence in the cooler tubes) and thermophoresis
- Compaction of the deposits due to thermophoresis and gas pulsation
- Water, sulphuric acid, hydrocarbons and nitrogen oxides are stored in the deposited layer due to the effects of condensation, diffusion and adsorption.
    - ⇨ Further compaction of the soot layer
- Balance of soot precipitation between aerodynamic forces and adhesive forces. (The fouling layer acts as insulation and reduces the temperature difference)

One variable to describe the loss of cooling capacity is the so-called fouling factor.

The thermal transfer portion of soot f_{soot} is known as the fouling factor in the heat transfer coefficient k (figure 2)

Übersetzung Formel:
$S_{Ruß} = s_{soot}$
$\alpha_{Gas} = \alpha_{gas}$
$\alpha_{Kühlmittel} = \alpha_{coolant}$
Der Fouling factor ergibt sich damit zu = The resulting fouling factor is
$F_{Ruß} = f_{soot}$
$\lambda_{Ruß} = \lambda_{soot}$

α_{gas}= heat transfer coefficient on the gas side
S = thickness of the wall or deposit
λ = heat conduction coefficient
$\alpha_{coolant}$ = heat transfer coefficient on the cooling medium side

Übersetzung Abb. 2:
$S_{Ruß} = s_{soot}$
$\alpha_{Gas} = \alpha_{gas}$
$T_{Gas} = T_{gas}$
Ruß Schicht = Soot layer
Kühlerwand = Cooler wall
Kühlmittel = Coolant
etc. s.o.

Figure 2*: Heat transfer coefficient k through a fouled cooler wall*

The design and hence the dimensions of the coolers are largely determined by the exhaust gas mass flows that have to be recirculated through the cooler. Recirculation rates over 40% are sometimes realised in cars but the absolute mass flow is so low that the coolers have only a small number of winglet tubes and are generally shorter than 200mm. Car exhaust gas coolers with bypass dampers are also available (figure 3). The damper is opened and the cooler bypassed during engine cold starts allowing the engine to heat up more quickly [7]. As a result, the oxidation catalyst converts hydrocarbon (HC) and carbon monoxide (CO) more quickly. Heavy-duty truck engines with a cubic capacity of 12 to 15 litres require much larger coolers with a length exceeding 400mm.

Figure ***3:*** *Car exhaust gas cooler with bypass damper*

Even though winglet tubes are less susceptible to fouling compared to other cooler designs their performance requirements rise steadily while package space remains constant [3]. In this case an oxidation catalyst in front of the EGR system may offer some advantages because it removes hydrocarbons from the exhaust gas and from the particles. Hydrocarbons cause soot adhesion on the heat exchanger surface because they condense out and form some kind of adhesive on the cold wall of the cooler. The sooting also affects the bypass damper and the EGR valve, which can become blocked in extreme cases.
Exhaust gas aftertreatment in the EGR tube is becoming more important, especially in view of new combustion processes, because HC raw emissions will increase in future.

3) Functions of EGR catalysts

EGR catalysts are designed as oxidation catalysts and positioned in front of the turbine. Under real driving conditions the temperatures in the manifold range from 200°C to 750°C depending on the amount of load. As mentioned above, the main purpose of the EGR catalyst is to convert gaseous and deposited hydrocarbons.
The conversion rate at high levels of HC raw emissions was assessed by first measuring the emissions from a naturally aspirated diesel engine, which was used as a test engine. Vehicle measurements were carried out on a roller test bench according to the new European driving cycle (NEDC). The dimensions of the catalyst were Ø 50 x 50.8mm, 200 cpsi with a precious metal loading of 90 g/ft^3. Modal emission measurements were taken in front of and behind the EGR catalyst. Figure 4 illustrates HC emissions in front of and behind the EGR catalyst and the temperatures in front of the EGR catalyst.

Übersetzung Abb. 4:
Zeit – Time
Conc. THC. vor AGR-Kat = Conc. THC in front of EGR catalyst
Conc. THC. nach AGR-Kat = Conc. THC behind EGR catalyst
Temp. vor AGR-Kat = Temp. in front of EGR catalyst
Gewinn = Gain

Figure 4: *HC emissions in front of and behind the EGR catalyst and temperatures in front of the EGR catalyst*

The catalyst lights off approx. 20 seconds after the engine starts. The conversion rate over the entire test is approx. 60%.

A cooler without an upstream EGR catalyst was aged on the engine test bench to assess the effects of the EGR catalyst on soot precipitation in the cooler. The soot deposits were subsequently analysed.
The cooler was dismantled into a sample approx. 70mm long and 20mm wide to determine the volatile soot particles. The sample was weighed and then inserted into a sealable, heatable quartz tube and subjected to a stream of nitrogen (50l/h). The tube was heated to the following set of temperatures:
Room temperature, 50, 100, 150, 200, 250, 300, 350, 400, 450 and 500°C
As soon as each set value had been reached the temperature was maintained for 45 minutes. The sample was then cooled and weighed.

After having determined the weight at 500°C, the nitrogen was replaced by air and the soot was burnt. The soot-free cooler sample was weighed and the soot quantity was calculated on the basis of the difference. The ash content of the soot was determined separately by burning a cooler sample of identical size and collecting the non-combustible components.
The portion of volatile organic compounds (VOC) for each temperature range corresponds to the cumulative reduction of weight between room temperature and 500°C with respect to the initial weight consisting of soot + VOC + ash.
Figure 5 shows the reduction of weight over the test temperature ranging from 20°C to 500°C.

Übersetzung Abb. 5:
Anzahl am Ruß = Portion in soot
Temperatur = Temperature

Figure 5: *Result of the soot analysis from an EGR cooler without an upstream catalyst*

This clearly shows that the soot contains approx. 40% VOC in coolers without upstream catalysts. This analysis leads to the conclusion that the EGR catalyst could convert approx. 40% of gaseous or deposited hydrocarbons, which would otherwise condense in the cooler.

4) Integrated EGR catalysts

In order to realise the shortest possible routes with the smallest degree of pressure loss the EGR cooler is usually positioned close to the manifold and the turbine. The lack of space in the engine compartment makes it difficult to install an EGR catalyst in the inlet pipe in front of the cooler to ensure optimum flow. Therefore an integrated solution was developed (figure 6) where the EGR catalyst is integrated directly in front of the cooler unit (zero gap) in the mantle of the cooler. Apart from the benefits relating to cost and package space, another advantage of this position is that it ensures optimum flow distribution through the EGR catalyst.

Figure 6: *System diagram of an exhaust gas heat exchanger with an integrated catalyst*

Figure 7 shows the flow distribution behind an exhaust gas cooler with an upstream catalyst.
Flow distribution was measured on a flow test bench. The air mass flow rate was 40kg/h at room temperature. The distribution itself was measured behind the exhaust gas cooler with the aid of a hot-wire anemometer.

Übersetzung Abb. 7:
Geschwindigkeit = Velocity

Figure 7: *Flow distribution measured on a car exhaust gas cooler with upstream EGR catalyst*

Since there is no gap between the catalyst and the cooler unit the exhaust gas and the pressure cannot equalise between the catalyst and the cooler. In terms of flow distribution in the catalyst this means that the flow is equalised not just by the very low dynamic pressure of the catalyst but also by the total pressure loss of the system consisting of catalyst and cooler. This significantly improves flow distribution and with it the utilisation rate of the catalyst because the dynamic pressure of the cooler is relatively high compared to that of the catalyst.
Flow distribution in the cooler is also greatly improved. This enhances the performance of the cooler and reduces thermal stresses in its floor. Coolers are frequently bolted to a 90° floor on the inlet side. Here, too, an oxidation catalyst helps to equalise the flow. In order to minimise any fouling of the bypass damper and the EGR valve the above-mentioned components must be positioned on the “cold side” in the EGR tube.

5) Test results

A cooler with and a cooler without an EGR catalyst were aged on a dynamic engine test bench to examine the improvement potential under realistic operations. The EGR catalyst (Ø 38 x 70; 200 cpsi; 0.080mm) had a Pt/Pd coating (150 g/ft^3).

The engine test bench is equipped with a three-phase asynchronous motor for a 4-quadrant drive. The test bench automation system CATS$_{NT}$ has an integrated real-time governing and control system based on a dSpace/Mathlab application to ensure highly dynamic engine and brake control. The test bench is fully air-conditioned providing controlled combustion air temperature, humidity and volume; room air temperature; extracted air and fresh air supply; and fuel condtioning. The CATS_{NT} automation system carries out all tasks relating to process control, monitoring, measurement, visualisation, driving profile processing, limit value monitoring, operational data log, data storage, data communication and, in part, control. The system works with a 100Hz internal clock and has inputs for NiCrNi and Pt100 temperature sensors, a variety of pressure measuring points, 0-10VDC analogue inputs and serial ports for the purpose of measurement data logging.

The fouling tests were carried out on a three-litre, 6-cylinder diesel engine. The exhaust gas system behind the turbocharger was designed to ensure that the exhaust gas is distributed equally to several exhaust gas streams via a V-piece so that several exhaust gas coolers could be tested simultaneously.

A separate cooling circuit was constructed to distribute equal amounts of cooling water to the coolers and provide accurate conditioning by heating and cooling the cooling water.

The system permits the measurement of exhaust gas temperatures and pressures in front of the oxidation catalyst and in front of and behind the cooler, and of coolant temperatures in front of and behind the cooler. Exhaust gas and soot were analysed with an AVL smokemeter for smoke value measurements, an AVL opacimeter for continuous opacimeter measurements and a two-channel Fast FID HFR500 for HC measurements (C_3).

This setup makes it possible to reproduce the test conditions very closely at different load points even with very different degrees of fouling and exhaust gas cooler designs.

***Figure 8**: Dynamic engine test bench for the aging of exhaust gas coolers*

Since the test bench setup includes a multiple distributor the exhaust gas extraction point is located behind the turbine in the engine exhaust gas system. This eliminates virtually all exhaust gas pulsations that would normally occur in the actual position in front of the turbine. Since stationary test cycles can give rise to unrealistic precipitation on the faces of the catalyst and the exhaust gas cooler, preference was given to a dynamic test cycle (figure 9). The engine data was adjusted to produce high soot emissions that would lead to sooting in a very short space of time.

Übersetzung Abb. 9:
Drehzahl = Engine speed
Drehmoment = Torque

***Figure 9:** Dynamic aging cycle for the aging of exhaust gas coolers*

During the test exhaust gas and cooler temperatures and pressure loss were recorded continuously. Figure 10 shows the pressure loss of the two test coolers. The initial pressure loss of the cooler with an EGR catalyst is only 20% higher than the pressure loss of the cooler without an EGR catalyst. This again underlines the fact that the pressure loss of the EGR catalyst is relatively small compared to the pressure loss of the cooler, as mentioned earlier in chapter 4, and highlights the flow distribution advantages of an integrated solution. After completion of the test the cooler with a catalyst lost an identical amount of pressure as the cooler without a catalyst.

Figure 11 shows the gas inlet side of the catalyst after completion of the test.

Übersetzung Abb. 10:
delta_p_Kühler_ohne_Kat = delta p cooler w/o catalyst
delta_p_Kühler_mit_Kat = delta p cooler with catalyst
delta_p = delta p
Testdauer = Test duration

***Figure 10:** Pressure loss of the two test coolers + pressure differential of each stream*

***Figure 11:** Catalyst inlet side*

There were no visible deposits on the catalyst. The cooler without an upstream catalyst showed more coating on the gas inlet side than the cooler with an upstream catalyst. The analysis of the temperature measurement behind the coolers revealed a temperature increase over the duration of the test and hence a fall in the resulting temperature difference over the cooler and thus a reduction in cooling capacity.

The reduction in cooling capacity of the cooler with an EGR catalyst was 6K less after a 160-hour endurance test (figure 12).

Übersetzung Abb. 12:
delta_T_Kühler_ohne_Kat = delta T cooler with or w/o catalyst
T_nach_Kühler_ohne_Kat = T behind cooler w/o catalyst
T_nach_Kühler_ohne_Kat = T behind cooler with catalyst
Etc. s.o.

Figure 12: *Resulting temperature difference over the coolers with and without EGR catalyst plus individual temperatures behind the coolers*

The cooling capacity of the cooler with a catalyst could be increased by approx. 10% through the use of an oxidation catalyst. Since this test setup involved cooler versions with an optimised cooling capacity it is safe to assume that the efficiency of the EGR catalysts is likely to increase with a standard cooler design. However, the tests also highlighted the need for further optimisation.

6) Summary

The EGR system plays an important role in reducing engine raw emissions. A reduction of combustion chamber temperatures primarily lowers the level of nitrogen oxide. Therefore the EGR system, consisting of recirculation tube, cooler and bypass damper, represents an emission-relevant component. The long-term stability of the cooling capacity and of the exhaust gas recirculation rate is of crucial importance. The development of an EGR cooler with an integrated catalyst offers a solution to reducing precipitation in the cooler especially in view of new homogeneous combustion processes with higher HC and CO emissions.
Analyses of the deposits and tests on a cooler aging test bench showed improvements to pressure loss and a smaller loss of cooling capacity where a catalyst was used.
The catalyst integrated in the EGR cooler therefore represents a solution that offers considerable advantages with respect to package space, flow distribution and cost.

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