Turbolcharger for emission concepts with low-pressure-end exhaust-gas recirculation (2007)
Introduction

Targeted further development, primarily on the injection system and the turbocharging system, has led to a state of development on the diesel engine that, as regards driving performance and fuel consumption, makes the diesel engine an attractive drive unit for private and commercial road traffic. This will be impressively substantiated in the years to come by increasing shares of the market. The disadvantages for the diesel engine, besides its comparatively high cost, are the high emissions of nitrous oxides and particulates owing to the way it functions. To date, it has been possible to meet the vehicle targets with feasible effort.

As regards achieving the short and medium-term consumption targets demanded – either voluntarily or by law -, i.e. for reduction of CO2 emission, the diesel engine is an important, indispensable module. Compliance with future legal emission targets for nitrous oxides and particulates however means that it faces a technological challenge. If the diesel engine, in future as well, is to achieve high market shares, it will be necessary to find reliably functioning solutions for compliance with the emission limits that can be implemented in series effectively, reliably and at feasible cost.

Exhaust-gas recirculation on the diesel engine

Even today, various primary and secondary measures, i.e. measures inside the engine and exhaust-gas aftertreatment components, are used to reduce the nitrous oxide emission of diesel engines. In future, besides development of new systems, the aim will be to combine the individual approaches in targeted manner and match them optimally. Mindful of the fact that over 50 % of nitrous oxide emissions are emitted in transient phases of the New European Driving Cycle, it can clearly be seen that questions relating to control technology are exceedingly important [1].

Recirculation of exhaust gas into the combustion chamber is a tried-and-tested measure for reducing nitrous oxides. Ultimately, the effect of this measure is, primarily, based on a reduction in the peak temperature, a reduction in the combustion velocity and a reduction in the partial oxygen pressure in the cylinder. Owing to the broad ignition limits on the diesel engine, recirculation rates of 60 % and more are possible in principle. In practice, however, the recirculation rates are limited by the available motive pressure gradient in the induction and exhaust gas pipe.
The potential of exhaust-gas recirculation increases with the recirculation rate and as low a temperature as possible of the recirculated exhaust gas. Besides exhaust-gas recirculation inside the engine, concepts implemented today tap the exhaust gas in the manifold upstream of the turbine of the turbocharger and admit it into the intake duct via a control valve upstream of the turbocharger compressor. This circuit arrangement is referred to as high-pressure-end exhaust-gas recirculation. The problems associated with this circuit arrangement include the limited recirculation rates, equal distribution of the exhaust gas over the individual cylinders and the fact that the recirculated exhaust gas is not available for relief in the turbine.

Better results and more advantages can be achieved by low-pressure-end exhaust-gas recirculation – tapping the exhaust gas downstream of the exhaust-gas cleaning section in particular downstream of the diesel particulate filter, and admitting the exhaust gas upstream of the compressor inlet [2,3,4,5]. While the specified problems of high-pressure-end recirculation do not occur here or at least occur in a less serious manner, it is the behavior in transient operating phases which is problematic here owing to the relatively long recirculation distances. Consequently, the greatest potential is attributed to a system that contains both high-pressure-end and low-pressure-end exhaust-gas recirculation.

However, to date, it has been necessary to ignore low-pressure-end exhaust-gas recirculation owing to the problematic effects on the compressor and the downstream components of the inlet section. Borg Warner Turbo Systems has solved this problem with its own fundamental research and in close cooperation with a vehicle manufacturer.

**Stressing the turbocharger owing to increased compressor inlet temperatures**

Even though the recirculated exhaust gas is generally routed via a cooler, compressor inlet temperatures are increased, i.e. the compressor conveys a higher volume flow rate at operating points with low-pressure exhaust-gas recirculation. The higher inlet temperature results in disproportionately high compression final temperatures and a higher work of compression. The gas outlet temperatures are limited by the permitted temperatures of the materials used, to approx. 210 °C in the case of aluminum alloys. The design of the turbocharger, the shaft-hub connection of the compressor impeller, the thermal integrity of the turbocharger or the materials used may need to be matched to the changed thermal boundary conditions. The material grey
cast iron is available as an alternative for the compressor housing. A titanium alloy such as used as standard for other reasons on certain turbochargers for commercial engines could be used as an alternative for the compressor impeller. However, this would lead to far higher costs.

**Stressing the turbocharger as the result of inhomogeneous flow at the compressor inlet**

The recirculated exhaust gas is added to the fresh air stream upstream of the compressor. In the case of nozzle admission, this results in hot strands depending on impulse ratio of the two material streams and the geometry of the mixing section. These hot strands have both thermodynamic and thermomechanical impact on the compressor components. Consequently, development of a turbocharger suitable for low-pressure exhaust-gas recirculation must include a detailed analysis of inflow to the compressor and mixing.

Mixing in practice must occur over as short a distance as possible owing to the limited space conditions in the engine compartment. Homogenous thorough mixing cannot be achieved if there is a simultaneous demand for low pressure losses. The pressure losses which impact on the overall efficiency, the thermodynamic state variables at the compressor outlet and the oil leakage of the turbocharger are very important. Certain, suitable nozzle admission variants or mixer fittings result in far more homogenous flow and temperature profiles over short distances than the simply connecting two pipes directly [6,7], however, even with this – owing to the greatly changing impulse ratios of both material streams – no completely homogenous flow profile can be achieved over the entire operating range of the engine on the mixing section available, so that flow inhomogeneities – such as hot strands – at the inlet of the compressor must be assumed [8]. This flow situation caused by LP-EGR was examined with numerical methods with the aim analyzing the flow through the compressor and determining what additional thermomechanical loads the compressor components (impeller and housing) must suffer as the result of flow with strands.

Figure 1, in viewing direction of the compressor impeller, shows a temperature distribution in a cross-sectional plane upstream of the compressor inlet as can occur at a specific operating point as the result of the radial nozzle admission of the low-pressure-end recycled exhaust gas over large openings of various sizes distributed over the circumference, openings, in the fresh air stream inducted by the compressor after a distance of approx. half a pipe diameter (TFreshair = 298 K, TND-EGR = 473 K, EGR rate = 33 %). You can clearly see 4 strands in the medium
temperature range (≈ 400 K) and a hotter strand (≈ 435 K) in addition to what is rather a cold zone extending through to the hub (≈ 293 K) stationary upstream of the rotating compressor impeller. This profile was determined in a numerical simulation of mixing of both material streams [8].

Figure 1: Temperature distribution at the compressor inlet (plane 0)

The calculation region consists of the compressor (impeller, housing) with an inflow and discharge section required for numerical reasons. The k-ε Reliazaible model is used as the turbulence model. The CFD simulation of the flow was performed in instationary manner in order to also map instationary effects owing to the inhomogeneous inflow and the rotor-stator interaction. The compressor speed was n=126,200 rpm and the compression ratio was approx. 1.6 in the cases under investigation.

Figure 2 clearly indicates the cross-sectional planes in the blade arrangement in which the temperature distribution is to be discussed below. Figure 2 (A) shows the temperature distribution directly at the inlet of the compressor. By comparison with the inlet profile (plane 0), the temperature cross-sectional profile changed only little and the mixing quality improves only little with increasing distance without further measures being taken [8]. The individual blade channels of the compressor continuously convey the inflow from flow tubes which have the form of circular ring segments. When moving over a stationary hot strand, a “packet” of the hot strand is “peeled” into the channel, a packet corresponding to the velocity conditions. When moving over a cold zone, this produces a corresponding “packet” with a lower temperature. Hot and cold flow packets which are conveyed by the diverging compressor channel then occur sequentially in
the compressor channel in accordance with the temperature cross-sectional profile of the inflow. The rotating impeller does work on the flow, when doing this transports the flow in the direction of rotation (Figure 2 (B)) and finally leave it in the diffuser when the individual flow packets (admission frequency = departure frequency) combine again to form strands (Figure 2 (C)). As expected, there is a homogenization of the cross-sectional temperature profile (A B C) to a certain extent as the result of cross exchange as the flow passes through the compressor, but there is no thorough mixing or mixing. A hot strand stationary in front of the compressor is drawn through impeller, diffuser and volute casing and influences the temperature distribution in the components (Figure 4 (A)). This is of no significance as regards equal distribution of the recirculated exhaust gas over the individual cylinders. This is because a largely homogenous mixing already occurs over the long distance to the cylinder inlet, not least the charge air cooler.
Besides an analysis of flow with strands through the compressor, the non-stationary flow simulation, in a following step, supplies the boundary conditions (temperature distributions near to the wall, wall thermal transfer coefficients) for the thermomechanical analysis. The FEM analysis serves to calculate the temperature and stress distribution in the impeller and in the compressor housing. A linear elastic material behavior is assumed. Practical assumptions were made for the boundary areas for which no temperatures were obtained from the flow simulation (Figure 2 (B)).

Formula:
- relative Spannung ... = Relative stress in respect of R
- Temperatur + Fliehkraft = Temperature + centrifugal force
- nur Fliehkraft = Centrifugal force only

Figure 3 : Stress distribution in the impeller

Figure 3 (C) shows the stress distribution in the impeller under the compressor operation load spectrum with inhomogeneous inflow. By comparison, Figure 3 (D) analyzes the stress state for the same operating point but with homogenous inflow temperature profile and centrifugal-force...
loading. It is clearly indicated that the stress state is impacted only unimportantly by the inhomogeneous temperature profile. If we refer stresses obtaining in the impeller at this operating point to the permitted Rp0.2 value (Figure 3 (A)) at the relevant temperature, it is clearly indicated that the stress limit of the material is exceeded at no point in the component under LP-EGR operation. This result is physically plausible with regard to the high speed of the impeller, i.e. the high-frequency rotation through the inhomogeneous inflow profile, in conjunction with the very good thermal diffusivity of the material used, required for fast temperature equalization within the component.

While the compressor impeller rotates at high frequency through the stationary hot and cold zones of inflow and thus experiences comparatively low temperature differences viewed over a circumferential line, there is an outflowing temperature profile (Figure 2 (C), Figure 4) in the volute housing of the compressor which is inhomogeneous over the circumference. Here as well FEM analysis must be used to clarify to what extent the boundary conditions resulting from LP-EGR reach the component’s stressing limits. Figure 4 shows the arithmetic grid of the compressor housing that is treated theoretically at the location of the central housing as permanently in place but is able to expand freely in radial direction. The temperature on the outside has assumed at a conservative 298 K.

Figure 4 : Near-wall temperature distribution in the volute and arithmetic grid
Figure 5: Temperature and stress distribution in the compressor housing

The temperature distribution in the housing (Figure 5) clearly indicates the influence of the thermally inhomogeneous outflow to the housing. However, the absolute temperature gradients are somewhat low so that the additional component loading caused by LP-EGR must be classified as moderate, not least owing to the moderate thermal admission as well and the good thermal conductivity of the aluminum alloy used. The absolutely highest stress occurring in the housing is around 15 MPa and is thus non-critical.

Stressing the turbocharger as the result of the constituents of the exhaust-gas-air mixture

The gas mixture to be conveyed, in addition to containing the inducted fresh air with its humidity, contains exhaust gas essentially consisting of the residual oxygen content, the products of combustion H2O and CO2 and the nitrous oxides (NOx, SO2, CO, uncombusted hydrocarbons) in small quantities, depending on fuel, combustion process and exhaust-gas aftertreatment, in addition to soot particles. It is necessary to allow for the engine oil admitted into the intake duct owing to closed-circuit crankcase venting.

In addition, the exhaust gas may entrain particles which do not originate from the combustion process but originate from the components of the exhaust-gas cleaning system, for example the ceramic matrix of the diesel particulate filter or the canning process of these components. These particles do, admittedly occur in reasonable quantities but they do occur over the entire lifecycle.
of the components and, at least partially, in forms and sizes that may be damaging. These particles are flushed to the intake end via the recirculation system.

**Droplet strike as the result of water condensation**

The water vapor contained in the exhaust gas, if the temperature drops below the dew point, may condense on the numerous “seeds” present, depending on the operating state of the engine and other boundary conditions. If these water droplets strike the metallic surfaces of the compressor impeller, they have a greatly erosive effect under certain circumstances, and this is referred to as droplet strike and must be avoided at all costs.

In order to avoid liquid phase from the low-pressure exhaust-gas recirculation system, the temperature of the recirculated exhaust gas should remain above the dew point temperature in all steady operating states. Below this temperature, there is a risk of condensation of liquid phase in the recirculation system. Water condensation on admixing of the EGR stream in the fresh air stream would only be anticipated at low ambient temperatures in stationary manner. Calculations and numeric simulations [8] indicate that the risk of droplet strike can be greatly restricted with a suitable design of the recirculation system and with a skilful application.

**Particulate strike**

Figure 6 shows the blade assembly of a compressor impeller made of aluminum after use on an engine with low-pressure exhaust-gas recirculation. Even without magnification, we can clearly see signs of damage whose intensity impact on the efficiency of the impeller. This blade assembly is covered with thin, resinous deposits. If we analyze the damage symptoms in greater detail under the scanning electron microscope, we can clearly see that virtually all damage has occurred on the front edge of the projecting blades with increasing intensity towards the tip of the blade.
This damage was caused by particulate strike. The larger the particles, the less they are capable of following the position of the flow owing to their inertia. This means that they impact at various angles on the blades. After we analyze the velocity conditions, we can clearly see that we can speak less of impact by particles on the compressor and more of a knocking out of the particles by the blade leading edges. This explains why virtually all damage caused by particles is found at the edges of the projecting blades.
The focus of development work into effective protection mechanisms lay not least for reasons of cost on retaining the compressor impeller material used. The focal point of the experimental investigation, besides assessing the adhesive strength by overspeed tests, was on strike of the compressor impellers rotating at high speed (circumferential velocity 510 m/s, compressor volumetric flow rate 0.11 m³/s, inflow temperature 20 °C) with suitable materials of defined composition and grain size distribution (Figure 7). For this purpose, a dosing unit was set up with which it was possible to add particles in defined and reproducible manner to the compressor inflow (Figure 8). The proportioned quantity of particles is supplied to the compressor inflow by means of a pulse of compressed air. A fitting inside ensures that the particle stream corresponds to the entire flow cross-section. The state of the surface of the impeller, the efficiency and the balance state of the moving parts were assessed both before and after the strike event.

![Dosing unit for dusts and single particles](image)

**Figure 8: Dosing unit for dusts and single particles**
Figure 9: Strike result on the uncoated compressor impeller

Figure 10: Effect of 4 x 0.25 g of Arizona dust on various coatings
Figure 9 (A) shows a finished, cast compressor impeller in accordance with the state of the art. The efficiency of this impeller is shown in Figure 8 (D, continuous curves). Clear abrasion marks can be seen at the inlet edges of the projecting compressor blades after four strikes each with 0.25 grams of “Arizona dust” (Figure 7). Figure 9 (B) shows the front edge of the blade after striking by 10 glass pearls (diameter 1 mm). The front edge of the blade is clearly subject to plastic deformation in the area of the impact.

Even though 10 particles were used, a total of more than 10 impacts are found in general, i.e. a particle can damage several blades until it, ultimately, has passed the blade assembly. While, after the strike with 4 x 0.25 grams of Arizona dust, the imbalance change remained within permitted limits, imbalance changes occur in the case of particles of this order of magnitude. The
back-check of the efficiency indicates a clear degradation which peaks at around two percentage points (Figure 9 (D), dashed curves).

The diversity of possible coatings is restricted by the permitted application temperatures of the basic material which may not be exceeded during the coating process, by the application temperature limit of the coating itself, by the coating process as regards the complex form of the impeller and by the required homogenous coating thicknesses which need to be achieved for reasons relating to impeller balance state. Various metal, ceramic, plastic and nanotechnology coatings were preselected, including a consideration of bi-coating systems and tri-coating systems as well. For reasons relating to extensive corrosion protection, the coating covers the entire impeller with the exception of the seat area of the impeller at the shaft collar and the seat area of the shaft nut.

Figure 10 shows the result of strike tests, each with 4 x 0.25 g of “Arizona dust” on impellers provided with various coatings (nano-paint, 10 μm thick, (A); Al2O3 (B); silicone (C)). All these layers were able to prove their adhesion properties with respect to the substrate in the overspeed test. After the strike, no closed layer was found in any of these coatings in the area of the blade front edge.

The nickel-phosphor coating (“chemical nickel”), deposited electrolessly with a thickness of 30 μm can be seen visually as the result of its silk-matt metallic gloss, Figure 11 (A). The efficiency of the impeller coated in this way (Figure 11 (B), continuous curves) corresponds to that of the uncoated impeller. Four strikes each with 0.25 of “Arizona dust” leave scratch marks on the front edge of the projecting blades but clearly in less pronounced manner than is the case on the uncoated impeller (Figure 11 (B)). It is particularly important that the coating not be pierced by this stressing and that a closed surface remain intact. The efficiency of the impeller (Figure 11 (D), dashed curves) corresponds, in practical terms, to that of the impeller prior to the strike event. The strike with 1 mm glass pearls pierces the 30 μm-thick protective layer (Figure 11 (C)). In this case, the coating breaks off locally limited around the impact point and the plastic deformation of the blades at the impact point is, in general, lower than with the uncoated blade.

The strike energy is dissipated partly by destruction of the layer and less so by plastic deformation of the base material. After strike of a particle of this order of magnitude, the protective effect of the coating is spent locally.

The nickel-phosphor coating proved, in the experimental investigations, to be best-suited to protect the compressor impeller. The coating endures multiple strikes up to a particle size of around 200 μm in a quantity occurring in practice without degradation of the efficiency, without inadmissible change to the balance state of the impeller and still retains corrosion protection. Particles upwards of a size of around 200 μm must be kept well away from the compressor by
taking other suitable measures. Separators or an additional filter in the LP-EGR line would be possibilities for this.

This nickel-phosphor planned for series launch is lead-free. It is produced at 90 °C without the action of an external current source by reduction of nickel ions available in an aqueous solution. The reaction partners are hydrophosphite ions which are also responsible for the phosphor content of the coating [9]. The phosphor content has a crucial impact on the characteristics relevant here – surface hardness and ductility. Deposition without external current guarantees an homogenous coating of constant thickness at all points of the surface and excellent mapping of the edges which is particularly important as regards the balance state of the impeller – if the bath composition is defined.

**Corrosion as the result of acidic condensate**

The composition of the exhaust-gas condensate and the dew point of the exhaust gas depend on the fuel composition, the combustion process, the air ratio, the load of the engine and on exhaust-gas aftertreatment. If condensate formation occurs, this causes pollutants contained in the exhaust gas to become detached and this generates strong acids which cause corrosive attack of the metallic surfaces. Above all, states in which fluid acidic concentrate can dwell and dry on the components are critical.
Figure 12: Result of the corrosion test

Event though aluminum is a relatively "unnoble" metal, its resistance to oxidation to relatively good. This is based on a thin, very firmly adhesive oxide layer which forms in a very short time on the metallically bare surface in the presence of oxygen. Aluminum is not attacked in acids which have an oxidizing effect, such cold nitric acid. However, aluminum does dissolve in strong acids, forming hydrogen and the corresponding salts which have an acidic reaction in aqueous solution. This is a rather slow process at first for as long as the protective natural oxide layer has dissolved. Decomposition then occurs more quickly.

Fundamental tests (salt spray test in accordance with DIN EN ISO 9227, Kesternich test in accordance with DIN 50018, assessment in accordance with DIN EN ISO 10289) were conducted to test various coatings for corrosion resistance.
Figure 12 (A) shows the result of a salt spray test with compressor housings coated with a nano-paint developed specifically for corrosion protection on aluminum surfaces (coating thickness around 10 \text{ m}). No signs of corrosive attack were visible after applying the salt for 250 hours to the housing. Figure 12 (B) shows the blade assembly of a compressor impeller coated with this nano-paint after a test in which the component was immersed for over 1,000 hours cyclically for 5 minutes in an exhaust-gas condensate bath (pH = 2.2) followed by 10-minutes drying phase. Even though the coating was attacked at points, the metallic surface, even after this large number of cycles, shows no corrosion attack. Table 1 shows the superiority of the nano-paint as regards its corrosion protection potential determined in the Kesternich test.

Owing to these results and owing to the good workability it is the obvious choice to use the nano-paint for all aerodynamic surfaces of the housing. The paint is sprayed onto the surfaces after specially pretreating the surface and obtains its definitive properties \cite{10} in a subsequent tempering process. The nano-paint procures its special characteristics from the size of its structures. The term “nanotechnology” covers structures smaller than 100 nanometer. In this order of magnitude, the surface properties increase continually in importance by comparison with the volume properties of the materials.

<table>
<thead>
<tr>
<th>Coating</th>
<th>Number of cycles until the occurrence of corrosion marks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel-phosphor (deposited electrolessly)</td>
<td>10</td>
</tr>
<tr>
<td>Al2O3 (deposited electrolytically)</td>
<td>4</td>
</tr>
<tr>
<td>Nano-paint (sprayed on and tempered)</td>
<td>30</td>
</tr>
</tbody>
</table>

**Table 1 : Result of the Kesternich test**

The nickel-phosphor coating used for the compressor impeller does not attain the corrosion resistance of the nano-paint. However, the nano-paint is worn away when subject to particulate erosion stressing so that the nickel-phosphor coating represents the best-suited solution overall with a view to the complex load spectrum acting on the compressor impeller. Figure 12 (D) shows an uncoated compressor impeller after a 60-hour salt spray test, Figure 12 (C) shows an impeller provided with the nickel-phosphor coating from the same test. Whilst the uncoated impeller shows clear crystalline deposits (salts) from the reaction of the aluminum with the acid and corrosion marks in the form of scars, the coated impeller shows an intact coating and a largely smooth, metallically glossy surface. The corrosive attack has an effect only in the area of
the uncoated mating surface of the shaft nut. Corrosive infiltration of the nickel-phosphor coating at the “coated – uncoated” borderline was not observed.

**Resinous deposits on the components**

Recirculated exhaust-gas constituents and the oil admitted as the result of inadequate separation from the closed crankcase ventilation, in conjunction with the increased temperature level at the compressor inlet or outlet, may form resinous deposits which adhere very firmly [11]. These deposits would be very undesirable because they reduce the flow cross-sections or may impede moving components in their function. Comparatively dry and non-firmly adhering deposits occurred in the tests conducted under the boundary conditions operated, and these remain with no impact on the reliability of the turbocharger. From the nanotechnology sector, there are approaches to create surface structures which have an oleophobic effect and are thus intended to prevent the tacky exhaust-gas constituents adhering, approaches involving targeted admission of certain element surface structures.

**Result**

If we consider the described additional loads at the boundary condition of application of turbochargers to date, i.e. homogenous, single-phase inflow to the compressor, we can clearly see the import of low-pressure-end exhaust-gas recirculation for the turbocharger. Nozzle admission of the recirculated exhaust gas, depending on EGR rate, fresh air mass flow rate and geometry of the mixing section, produces flow inhomogeneity in the compressor inflow, for example hot strands, continuing through the compressor impeller, the diffuser and the outlet from the volute housing. Under the boundary conditions obtaining, the additional thermomechanical loading of the rotating and stationary compressor components however remains uncritical as the result of the strandy flow.

![Figure 13 : Compressor impeller after 300 hours of engine run with LP-EGR](image)
Certain components contained in the exhaust gas result in an additional load for the turbo compressor. While droplet strike from condensation of water contained in the exhaust gas in a hot operating state can very largely be avoided by appropriate design of the system and suitable application, the erosive effect of particulates contained in the exhaust-gas stream, most of which do not originate from the combustion process, can be coped with by coating the compressor impeller ("chemical nickel"). In addition, this coating protects the compressor impeller reliably against the corrosive effect of acidic diesel exhaust-gas condensate.

The solution approaches for an exhaust-gas-resistant compressor, obtained both numerically and experimentally, were tested on a 300-hour engine test run at various operating points under real boundary conditions. The compressor impeller is characterized by a few, dry, non-firmly adhering deposits which do not impair the function of the compressor (Figure 13). The back-check of the imbalance state of the rotor and that of the compressor efficiency did not result in inadmissible changes by comparison with the original value. The REM analysis of the compressor impeller shows slight particulate marks on the front edges of the blades, but the coating at this highly stressed point is closed and thus intact (Figure 13). Corrosion marks were found neither on the compressor impeller nor on the compressor housing.

The results of the engine endurance run confirm the measures elaborated in the fundamental tests. They make a crucial contribution towards reliably mapping an exhaust-gas-resistant turbocharger compressor, the key component for implementing low-pressure-end exhaust-gas recirculation in series.
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