Diesel Engines with Low-Pressure Exhaust-Gas Recirculation

Challenges for the Turbocharger

Excellent driving performance and low fuel consumption make the diesel engine an attractive power unit for road traffic. It is an essential component for achieving fuel consumption targets demanded in future. The disadvantages of the compression ignition engine are the high, function-related nitrogen oxide and particulate emissions, in addition to costs. Compliance with future emission standards poses a technological challenge for it. Intensive experimental and numerical work allowed BorgWarner Turbo & Emissions Systems to determine the relevant influencing parameters of low-pressure-circuit exhaust-gas recirculation for the turbocharger and develop measures to protect the aerodynamic components in targeted manner. These measures would lead to anticipate that series use of low-pressure-circuit exhaust-gas recirculation would appear realistic as a contribution to further reducing pollutant emissions of the diesel engine.

1 Introduction

Exhaust-gas recirculation to the combustion chamber is a proved and tested measure for reducing nitrogen oxides. To date, the exhaust gas is tapped at the high-pressure end, that is tapped from the manifold, and admitted or recirculated downstream of the compressor. In specific areas of the engine map, advantages [1, 2, 12] can be achieved if the exhaust gas is recirculated in the low-pressure circuit. For this purpose, the exhaust gas is tapped downstream of the exhaust gas aftertreatment chain and admitted into the intake line upstream of the compressor. In this case, it is primarily the higher mass flow through the turbine and the associated higher efficiencies, the impellent pressure gradient available over a broad range for recirculation and the more homogenous mixing of the exhaust gas with fresh air that have an advantageous impact. However, low-pressure-end exhaust-gas recirculation was unable to be implemented reliably to date owing to the high load of the compressor.

2 Load Spectrum and Approaches to Solving the Problem

2.1 Increased Temperature Level and Flow Conditions at the Compressor Inlet

Feed-in of the exhaust air results in increased compressor inlet temperatures despite the fact that the exhaust air is cooled. These increased compressor inlet temperatures result in disproportionately high outlet compression temperatures. The design of the turbocharger, the shaft-hub connection of the compressor impeller or the materials used may need to be adapted to the changed thermal boundary conditions.

Hot strands that impact both thermodynamically and thermomechanically on the compressor components occur during feed-in of the recirculated exhaust gas, depending on the impulse ratio of the two material streams and the geometry of the mixing line. In practice, mixing can occur only over as short a distance as possible owing to cramped space conditions in the engine compartment. The pressure losses that have a negative influence on the overall efficiency, the thermodynamic state variables and the compressor outlet and oil leakage of the turbocharger are of crucial significance in this respect.

Numerical methods were used to investigate various mixer geometries in respect of their suitability in principle. One aspect that is of particular interest in this case is the distance after which an adequate mixing quality occurs with pressure losses that are as low as possible. The local mixing quality ε_i [3] that is a measure of the linear deviation of the local temperature T_i in the single cell from the adiabatic mixing temperature T_{adb} is used for assessing the mixture:

$$\varepsilon_i = \begin{cases} \dfrac{T_i - T_{Ab}}{T_{adb} - T_{Ab}} & for\ \ T_{Ab} < T_i < T_{adb} \\ \dfrac{T_i - T_{Fl}}{T_{adb} - T_{Fl}} & for\ \ T_{adb} < T_i < T_{Fl} \end{cases} \qquad \text{Eq. (1)}$$

$$T_{adb} = \frac{\dot{m}_{FL} \cdot T_{Fl} + \dot{m}_{Ab} \cdot T_{Ab}}{\dot{m}_{Fl} + \dot{m}_{Ab}} \qquad \text{Eq. (2)}$$

The global mixing quality ε allows a statement to be made on the mixing quality ε_i in one cross-sectional plane.

$$\varepsilon = \frac{1}{n} \cdot \sum_{i=1}^{n} \varepsilon_i \qquad \text{Eq. (3)}$$

Since the flow profiles under investigation have no homogenous velocity profile, the local mixing qualities ε_i were weighted with the mass flows in the individual cells.

$$\varepsilon = \frac{\sum_{i=1}^{n} \varepsilon_i \dot{m}_i}{\sum_{i=1}^{n} \dot{m}_i} \qquad \text{Eq. (4)}$$

$\varepsilon_m = 1$, in this connection, means complete mixing and $\varepsilon_m = 0$ means no mixing at all. The pressure losses are taken into consideration by the nondimensional index c_{pl}.

$$c_{pl} = \frac{p_{tot,ref} - p_{tot,i}}{p_{tot,ref}} \qquad \text{Eq. (5)}$$

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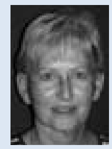

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Table 1: Operating points

Operating point	T_{Fl}	T_{Ex}	EGR rate
1	20 °C	200 °C	33 %
2	20 °C	200 °C	20 %
3	20 °C	200 °C	10 %

Where

$$p_{tot,ref} = \frac{\int_{A_{Ab}} p_{tot} \cdot \rho \cdot u \cdot dA + \int_{A_{Fl}} p_{tot} \cdot \rho \cdot u \cdot dA}{\int_{A_{Ab}} \rho \cdot u \cdot dA + \int_{A_{Fl}} \rho \cdot u \cdot dA} \quad \text{Eq. (6)}$$

$$p_{tot,i} = \frac{\int_{A} p_{tot} \cdot \rho \cdot u \cdot dA}{\int_{A} \rho \cdot u \cdot dA} \quad \text{Eq. (7)}$$

$p_{tot,ref}$ is a mass-weighted pressure that comprises the total pressures $p_{tot,Fl}$ and $p_{tot,Ex}$ in the two lines upstream of the mixing point, $p_{tot,i}$ is the mass-weighted total pressure in the relevant planes. The higher the pressure losses, the larger will be the values of cpl . The calculations are based on the values listed in **Table 1**.

For the sake of simplicity, we shall initially treat both material streams as dry air. There is a manifold whose secondary vortex structure has a positive impact on mixing located upstream of the mixing point in order to allow simulation under realistic boundary conditions. The turbocharger stream is admixed perpendicularly to the fresh air stream [4] in the first variant investigated, **Figure 1**.

The characteristic of total temperature is used as the indicator of mixing quality. The mixing quality ε_m over the mixing distance x/D shows a very shallow characteristic, i.e. a low increase in mixing quality ε_m over distance, **Figure 2**.

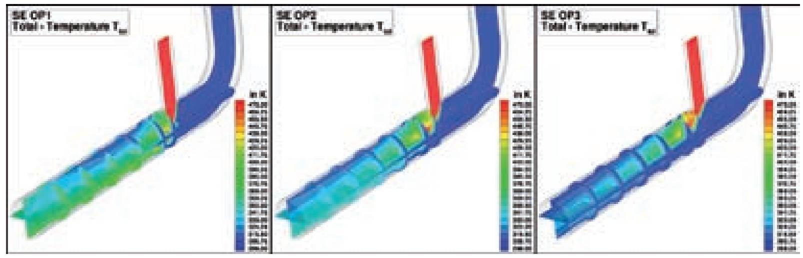

Figure 1: Distribution of the total temperature for perpendicular nozzle injection (SE)

Hot strands of various strengths form in the mixing line depending on mass flow ratio, that is impulse ratio, Table 1. The impulse ratio is one of the defining parameters with this type of mixing ("jet in crossflow") [5, 6]. This simple, blunt nozzle injection does not allow adequate mixing to be achieved over short distances and with low pressure losses. In the case of the radial mixer (RM), an annular chamber all-round hugs the fresh air tube, **Figure 3**. The exhaust gas is admitted through various bores on the circumference [7]. The lobed mixer (BM) consists of a circular array of folds that guide the core stream outwards and the casing stream inwards, consequently creating large shear planes between both material streams, **Figure 4**.

Variants RM and BM indicate a far greater rise in mixing quality over distance by comparison with SE, Figure 2. The BM proves to be less dependent on the mass flow ratio than the RM. Strands that are far less distinct occur on both mixers, consequently achieving a far more homogenous flow at the compressor inlet. Even after a distance of only x/D=1, mixing qualities exceeding 80 % occur, depending on operating point and type of mixer. The BM features the lowest pressure losses. **Table 2** shows a qualitative comparison of the mixer geometries investigated. One disadvantage of the BM is that, as a component installed in the main duct, it also continuously influences flow even at operating points without low-pressure exhaust-gas

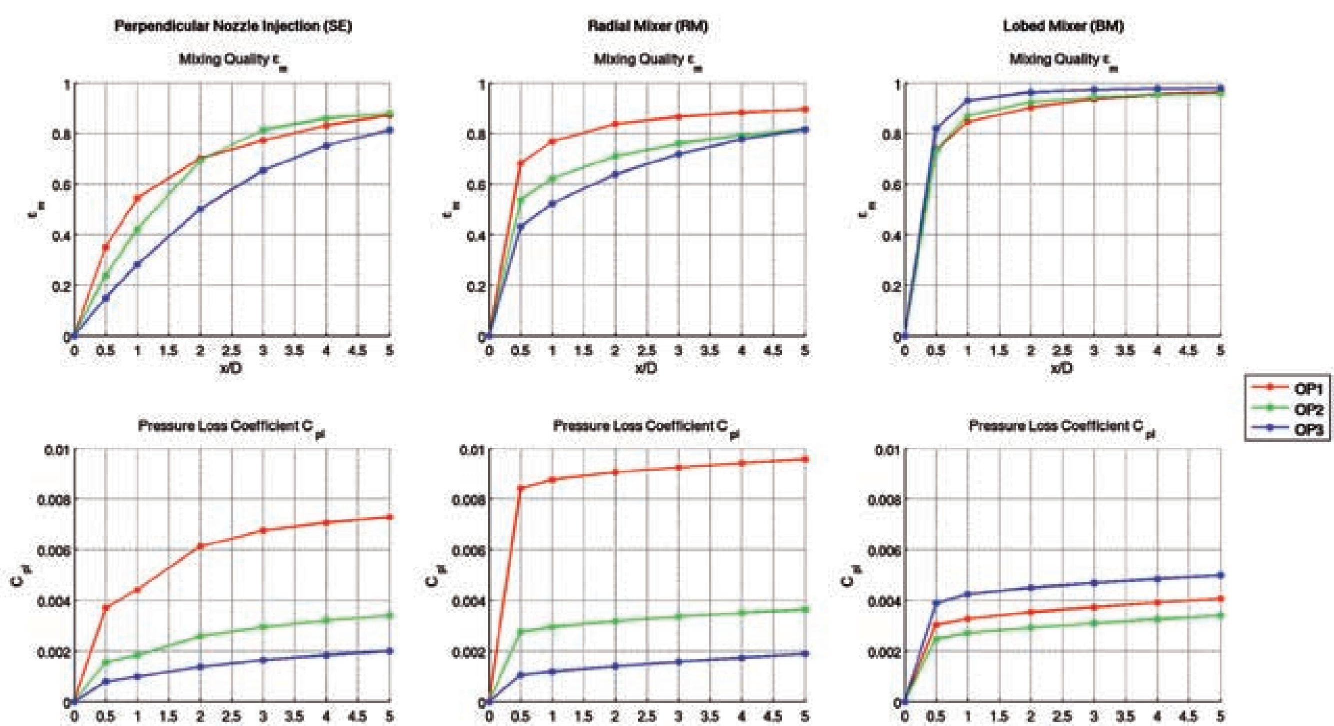

Figure 2: Mixing quality ε_m and pressure loss coefficient c_{pl} for various mixers

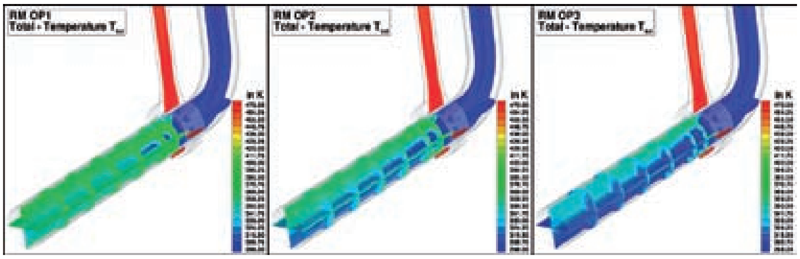

Figure 3: Distribution of total temperature for the radial mixer (RM)

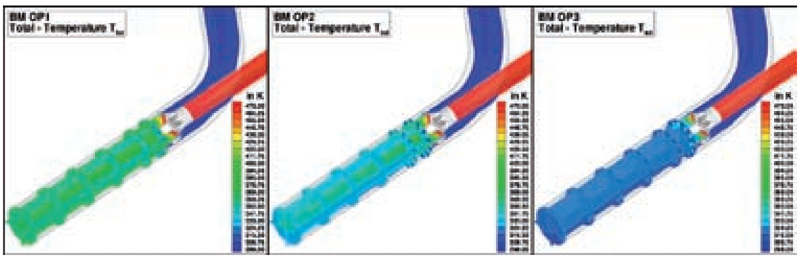

Figure 4: Distribution of total temperature for the lobed mixer (BM)

Table 2: Assessment of mixers

Mixer	Mixing quality	Pressure loss	Independence from operating point	Complexity
SE	–	+	–	++
RM	++	–	–	+
BM	++	++	++	–

recirculation. In practice, a series solution, as a compromise, will be based on the available installation space, pressure losses and, not least, cost. At this point, we should mention that flow inhomogeneities are generally propagated through the compressor and persist downstream of the compressor. The thermomechanical effects of the hot strands on the compressor impeller and on the compressor housing remain uncritical under the prevailing boundary conditions [8].

2.2 Elements of the Exhaust Air Mixture

The gas mixture to be conveyed contains exhaust gas that essentially consists of residual oxygen content, the combustion products H_2O and CO_2 and slight quantities of pollutants contained, depending on fuel, combustion behaviour and exhaust gas aftertreatment (NO_x, SO_2, CO and unburned hydrocarbons) and soot particulates, besides the fresh air inducted with its water content. The engine oil admitted into the intake duct as the result of a closed crankcase ventilation system must also be taken into consideration.

The exhaust gas may also contain particulates that originate not from the combustion process but from components of the exhaust gas aftertreatment, for example from the ceramic matrix of the diesel particulate filter or from the production process used to manufacture these components. These particulates do, admittedly, occur in relatively small quantities but they do occur over the entire lifecycle of the components and they do occur, in part, in shapes and sizes that may cause damage. These particulates are flushed into the intake line via the recirculation line.

2.2.1 Droplet Strike Owing to Water Condensation

Depending on process management, operating state of the engine and other boundary conditions, the water vapour contained may condense on the numerous condensation cores present if the temperature drops below the dew point.

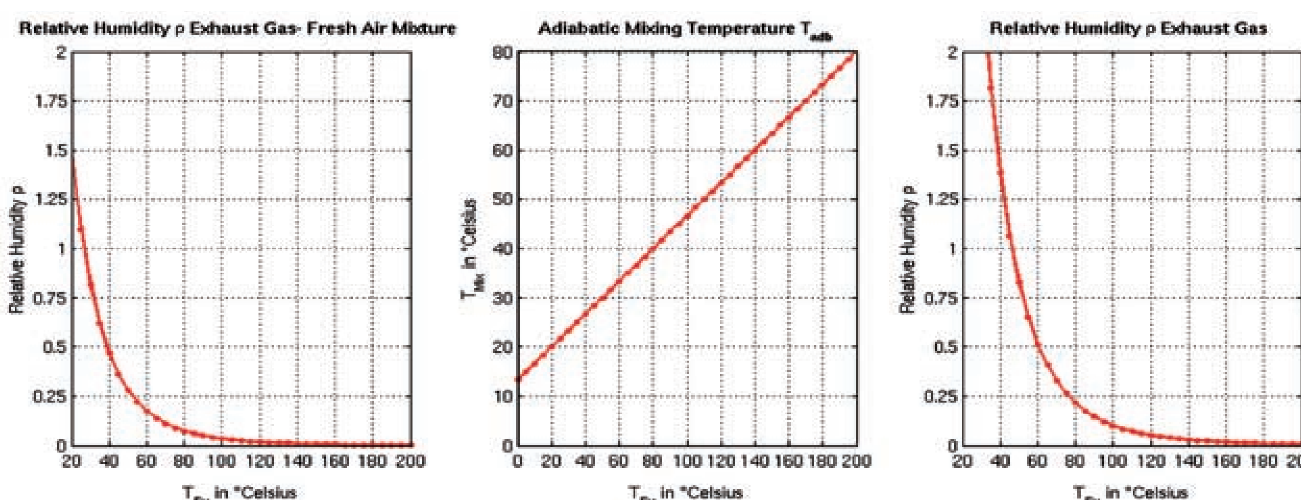

Figure 5: Relative humidity φ of the exhaust gas-fresh air mixture

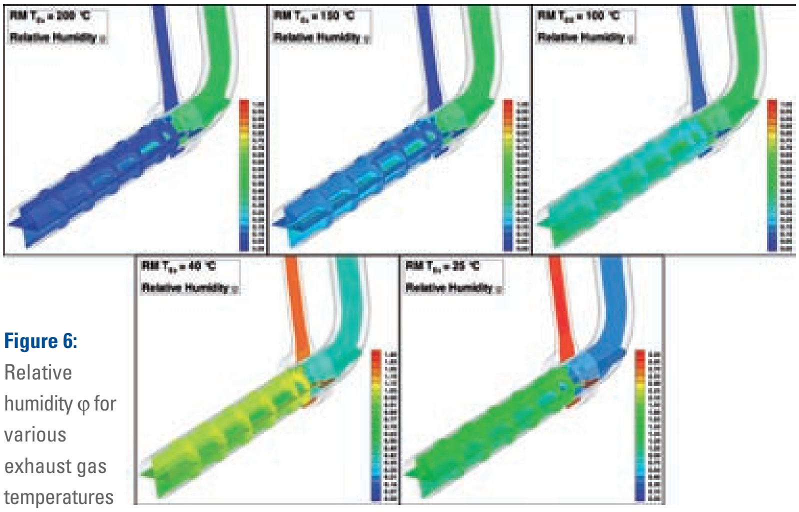

Figure 6: Relative humidity φ for various exhaust gas temperatures

Depending on ambient conditions, these droplets may grow, coagulate with other droplets or even evaporate. Liquid wall films may form, that droplets may enter but that they may also be torn from. These processes are very complex in practice. If droplets strike metallic surfaces at a high relative velocity or at unfavourable angles, they have a high erosive effect, generally referred to as “droplet hit”.

The particular boundary conditions under which liquid phase may form from the exhaust gas/fresh air mixture is of major significance. A combustion calculation was conducted in order to determine the water content of the exhaust gas. The combustion calculation indicates an absolute humidity of around 6.4 % on the basis of a relative humidity φ of the surrounding fresh air of 60 % at an ambient temperature T_{amb} = 20 °C and with a combustion air ratio λ = 1.4. On the basis of this information, it was possible to determine the relative humidity φ of an homogeneously mixing exhaust gas/fresh air mixture. **Figure 5** shows the relative humidity φ as a function of the adiabatic mixing temperature T_{adb} at an exhaust gas recirculation rate of 33 % and an air temperature of T_{Fl} of 20 °C.

Saturation, that is a relative humidity φ = 1 of the mixed gases, is achieved at a temperature T_{Mix} ≈ 27 °C, corresponding to an exhaust gas temperature T_{Ex} = 40 °C, Figure 5. At an exhaust gas temperature T_{Ex} = 40 °C, the relative humidity in the exhaust gas is already φ = 1.4, and this would result in condensation prior to mixing. Condensation of liquid phase by mixing of the two mass streams and the associated temperature reduction can consequently be considered uncritical at the corresponding exhaust gas temperature T_{Ex}. An exhaust gas temperature T_{Ex} below 40 °C (after cooler) must be avoided with regard to the risk of droplet strike.

This consideration is based on homogeneous mixing of the two part mass streams. An air-water vapour mixture was considered in order to establish whether points at which the flow is supersaturated can form locally as the result of flow inhomogeneities, and the exhaust gas temperature was varied at constant fresh air temperature (T_{Fl} = 298K). The results are shown in **Figure 6**. The results show the distribution of the relative humidity φ for the RM in operating point 1, Table 1.

Despite inhomogeneous flow, no values of $\varphi \geq 1$ occur in the mixing line. However, if the exhaust gas is saturated or supersaturated, values of $\varphi \geq 1$ occur in the mixing line as well. Downstream of the mixing point, the relative humidity φ drops. Droplet hit in through-heated state can be avoided with appropriate design and control of the recirculation line. Liquid phase may occur from low-pressure exhaust gas recirculation only during cold starting and at extremely low ambient temperatures.

2.2.2 Particulate Hit

Figure 7 shows the blades of a compressor wheel made of aluminium after operation on an engine with low-pressure exhaust-gas recirculation. Even without magnification, clear damages are visible, and these damages, at this intensity, impact on the impeller’s aerodynamics. If the damage symptoms are analyzed more precisely under the scanning electron microscope, it can be clearly seen that virtually all damage has occurred on the leading edge of the projecting vanes with increasing intensity in the direction of the vane tip.

These damages were caused by particulate hit. The larger the particulates, the less they are able to follow the flow owing to their inertia. This means that they strike the vanes at various angles. An analysis of the velocity conditions indicates that what is involved is less a strike of the compressor blades by the particulates but more a situation in which the particulates are knocked out of the intake stream by the leading edges of the vanes. This explains why practically all damage resulting from particulates is detected at the edges of the projecting vanes.

One focus in development of effective protection mechanisms was on retaining the material used, not least for reasons

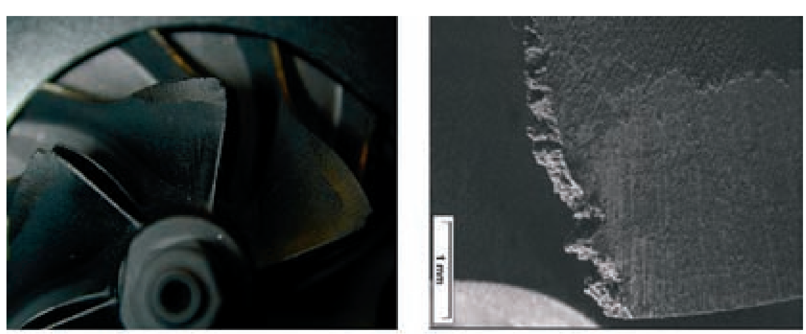

Figure 7: Particulate strike damage on the compressor impeller

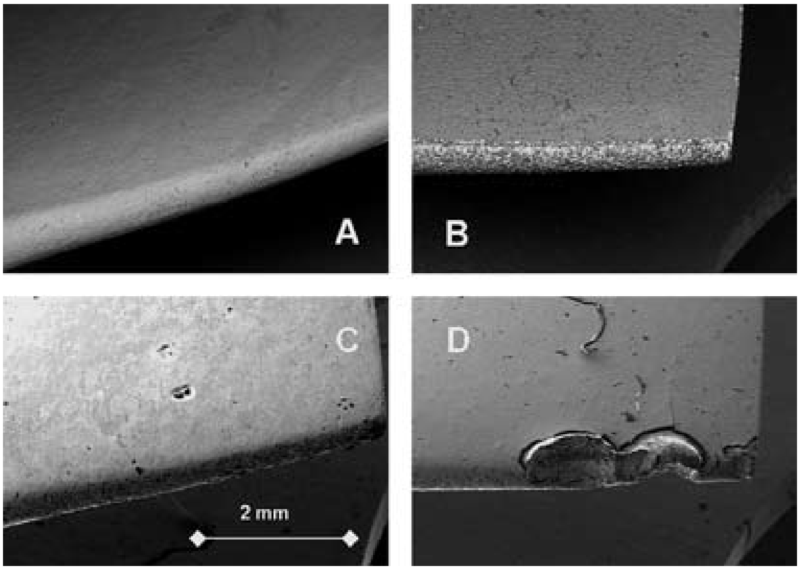

Figure 8: Vane leading edges before and after particulate strike

Table 3: Result of the Kesternich test

Coating	Number of cycles withstood until occurrence of defined corrosion marks
Nickel-phosphorous (electroless deposition)	10
Al_2O_3 (electrolytic deposition)	4
Nanopaint (sprayed on and tempered)	30

relating to costs, so that the main attention was paid to finding a suitable coating. Various metal, ceramic, plastic and nano-coatings were applied to aluminium impellers, and bi-coating systems and tri-coating systems were also investigated. The focus was on striking the compressor impellers rotating at high speed with suitable materials of defined composition and grain size distribution (Arizona dust SAE J 726 and spherical single particulates), besides assessing the adhesive strength of the coatings in overspeed tests. These materials were added in defined manner using a dosing unit, after which the condition of the surface of the impeller, the efficiency and the balance quality of the moving parts was assessed before and after the strike event.

Figure 8 (A) shows a vane leading edge in original condition. Figure 8 (B) shows a vane coated with Al_2O_3 and Figure 8 (C) shows a vane coated with nickel-phosphorous, each after a strike test with 4 x 0.25 g „Arizona dust“. While the nickel-coated vane (C) shows only slight wear marks on an otherwise intact and closed coating surface that have no impact on function or reliability, the coating in (B) in the area of the leading edge is completely eroded. Individual particulates with a size of 1 mm also penetrate the nickel-phosphorous coating, Figure 8 (D), and cause plastic deformation at the vane edges.

The nickel-phosphorous coating proves to be the best-suited for the compressor impeller in the experimental investigations. This lead-free coating is produced at 90 °C with no need for an external current source by reduction of nickel ions present in aqueous solution. The reaction partners in this case are hydrophosphite ions that are also responsible for the phosphorous content of the finished coating. The phosphorous content crucially influences the relevant properties of surface hardness and ductility [9, 10]. With a defined bath composition, external electroless deposition ensures a homogeneous coating of constant thickness at all points on the surface and excellent definition of the edges that is particularly important with regard to aerodynamics and balance quality of the impeller.

The nickel-phosphorous coating used withstands multiple strikes up to a particulate size of around 200 μm in quantities occurring in practice with no degradation of efficiency, without inadmissible change to the balance of the impeller and retaining corrosion protection (Section 2.3.3). Particulates upwards of a size of around 200 μm must be kept away from the compressor using other suitable measures.

2.2.3 Corrosion as the Result of Acid Condensate

The composition of the exhaust gas condensate and the dew point of the exhaust gas depend on the fuel composition, the combustion characteristics, the air ratio, the load of the engine and the type and performance of exhaust gas aftertreatment. If condensation occurs, pollutants contained in the exhaust gas become dissolved and this produces strong acids that result in corrosive attack of the metallic surfaces. It is, above all, conditions in which liquid acid condensate dwells on the components and is able to dry at the surface are critical. Fundamental tests (Kesternich test in accordance with DIN 50018, assessment in accordance with DIN EN ISO 10289) were conducted to test various coatings for corrosion resistance, **Table 3**.

Admittedly, the nickel-phosphorous coating used for the compressor wheel does not achieve the corrosion resistance of the nanopaint but the nanopaint is not adequately resistant to particulate hit. However, the nanopaint is used for all aerodynamic surfaces of the housing owing to its excellent corrosion protection properties and its ease of use. This paint is sprayed on to the complex-shaped components after special surface pretreatment and then develops its final properties in a following tempering process [11].

2.2.4 Resinous Deposits on the Components

Recirculated exhaust gas constituents and the oil admitted from the closed crankcase ventilation system as the result of inadequate separation may form

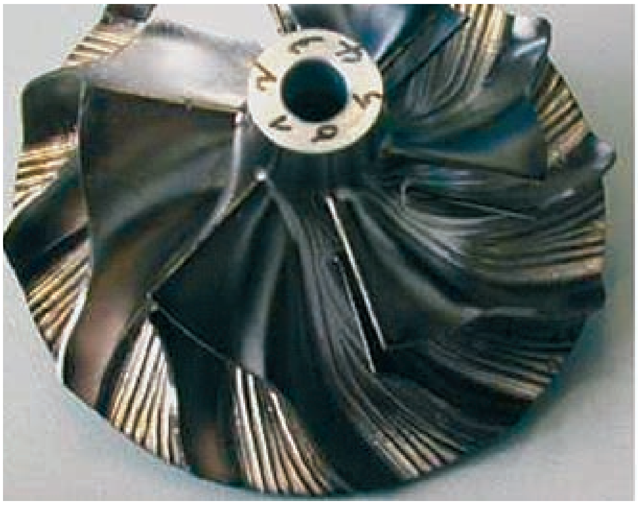
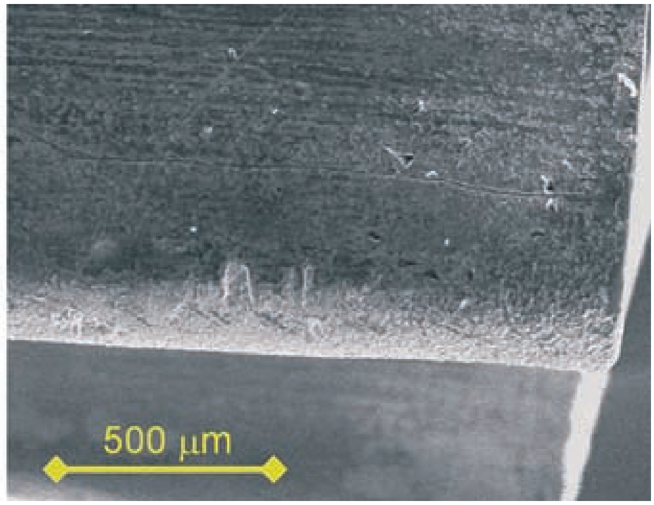

Figure 9: Milled compressor impeller after 300-hour engine run with low-pressure EGR

resinous deposits that adhere very strongly in conjunction with the increased temperature level at the compressor inlet or outlet. These deposits would be very undesirable since they may reduce flow cross-sections or cause moving components to seize. The nanotechnology sector provides us with approaches involving the creation of suitable surface structures by targeted incorporation of specific elements with an oleophobic effect, consequently aiming at preventing adherence of the sticky exhaust gas constituents.

3 Result and Synthesis

If we reflect the described, additional loads at the boundary conditions to date for designing turbochargers, that is homogeneous, single-phase inflow to the compressor, we can clearly see the impact of low-pressure-circuit exhaust-gas recirculation for the turbocharger.

The approaches to solving the problem, both theoretical and established experimentally, for the exhaust gas-resistant compressor were subjected to a real loading spectrum in a 300-hour engine test at various operating points. The result confirms the measures elaborated in the fundamental tests. The impeller shows only a few dry deposits that do not adhere strongly and that do not impair the functions of the compressor, **Figure 9**. The back-check of the balance quality of the rotor and the compressor efficiency indicated no inadmissible changes by comparison with the original values. The SEM analysis of the compressor impeller shows slight particulate traces at the vane leading edges, but the coating at these highly stressed points is closed and consequently intact. Corrosion marks were not found either on the compressor impeller or on the compressor housing.

Intensive experimental and numerical work allowed us to determine the relevant influencing parameters of low-pressure exhaust-gas recirculation for the turbocharger and develop measures to protect the aerodynamic components in targeted manner. These measures would lead us to anticipate that series use of low-pressure-circuit exhaust-gas recirculation would appear very realistic as a contribution to further reducing pollutant emissions of the diesel engine.

References

[1] Müller, V.; Christmann, R.; Münz, S.; Gheorgiu, V.: „System Structure and Controller Concept for an Advanced Turbocharger/EGR System for a Turbocharged Passenger Car Diesel Engine.“ In: SAE 2005-01-3888

[2] Tietze, T.; Lautrich, G.; Sommer, A.; Jeckel, D.; Ferrari, S.; Cancalon, P.J.: „Frischer Wind für den Pkw-Dieselmotor in Nordamerika: Niederdruck-Abgasrückführung als ein Baustein zur Bewältigung der Abgasemissionsvorschriften“ In: 11. Aufladetechnische Konferenz 2006, Dresden

[3] Dörr, T.: „Ein Beitrag zur Reduzierung des Stickoxidausstosses von Gasturbinen-Brennkammern.“ Dissertation, TU-Darmstadt, 1995

[4] Brune, K.-H.; Stoffel, B.; Matyschok, B.; Münz, S. CFD-analysis of the flow consisting of two mass flows with different temperatures and/or two phases in a turbocompressor FEDSM2006-98027

[5] Holdeman, J.D. Mixing of Multiple Jets With A Confined Subsonic Crossflow. Prog. Energy Combust Sci. 1993; Vol 19, pp31-70

[6] Oechsle; V.L.; Mongia, H.C.; Holdeman, J.D.: “A Parametric Numerical Study of Mixing in a Cylindrical Duct”. In: AIAA 92-3088, 1992

[7] Junfei Y.; Deschatrettes, N.; Ocean H.; Renaud, P.: “Compact Long-Route Exhaust Gas Recirculation Mixer Design and Optimization.”

[8] Münz, S.; Römuss, C.; Schmidt, P.; Brune, K-.H.; Schiffer, H.-P. „Turbolader für Emissionskonzepte mit niederdruckseitiger Abgasrückführung – Grundlagenuntersuchungen und Maßnahmen zur Ertüchtigung des Laders“. In: 12. Aufladetechnische Konferenz, 2007, Dresden

[9] Die AHC-Oberfläche – Handbuch für Fertigung und Konstruktion, 4. Auflage, 1999

[10] Holländer, A.: „Bleifreie Chemisch-Nickel-Verfahren und Ihre Eigenschaften“. In: MO Metalloberfläche, Ausgabe 01-02, 2004

[11] Wagner, G.: „Nanotechnologie in modernen Beschichtungsmaterialien aus lackchemischer Sicht“. In: Phänomen Farbe, Ausgabe unbekannt

[12] Weber, O; Jörgl, V.; Shutty, J.; Wenzel, W.: “Taming the Complexity of Future Air Breathing Systems by Smart Engineering” In: 7. Internationales Stuttgarter Symposium, März 2007

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