Effect of Water Droplets Caused by Low Pressure EGR on Spinning Compressor Wheels

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Abstract: The number of low pressure (LP) EGR applications will increase in future due to the challenging targets of upcoming emission legislations. The recirculating exhaust gas mixed with the fresh air upstream of the compressor inlet will face the turbocharger with several challenges. This study focuses on the influence of condensate in the form of water droplets hitting the spinning compressor wheel. As the liquid water from condensation may enter the compressor of the turbocharger in various forms, e.g. droplets with different sizes or as a wall film the first part of the investigation aims to investigate the influence of the admission type of water on the performance and damage of the wheel. In the second part with an increased cumulated amount of water and constant droplet size the circumferential speed of the compressor wheel was varied to locate areas in the operating range of the compressor which are vulnerable to damage. The resulting change in compressor performance is analyzed by continuous tracking as well as an evaluation of the steady state efficiency at regular operation before and after the tests. After the admission with water changes in surge and choke limits due to the damage are also investigated. Furthermore, the wheels are inspected visually and by scanning electron microscopy (SEM) and possible changes in balancing are studied. To ensure safe operation of the compressor wheel even under engine conditions where droplets can occur, one potential countermeasure is tested and presented in this study.

Key Words: Low Pressure EGR, Water, Droplets, Condensation, Compressor, Turbocharger, Coating;

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1 Introduction

New legislation rules pertaining to automobiles for 2020 and beyond imply challenging targets: low \( \text{CO}_2 \) emissions and low pollutions [1].

![Figure 1: Trend of \( \text{CO}_2 \) emissions [1]](image)

Figure 1 shows the worldwide trend of \( \text{CO}_2 \) emissions for all major markets. It can be seen that the USA as a traditional gasoline market for passenger cars have to invest relatively more than Europe to meet their respective targets. \( \text{CO}_2 \) emission reduction may concern diesel engines as well as gasoline engines as both still play a major role for propulsion and will continue to do so in the future [2].

For many years now, in combustion concepts a big portion of engine exhaust gas is led back to the combustion process, having positive effects on \( \text{CO}_2 \) emissions and pollutions. This method is called exhaust gas recirculation (EGR). In gasoline engines with stoichiometric operation the additional EGR flow leads to de-throttling of the engine at part load resulting in less pumping losses with a positive effect on \( \text{CO}_2 \).

In general a charge mixture including an (inert) EGR portion ignites slower than without EGR. Accordingly, ignition timing can be advanced towards an optimum. Thus, applied at full load, EGR will be a good measure for knock mitigation with positive effects on \( \text{CO}_2 \), too [3]. For diesel engines the application of EGR is mainly targeted on reducing engine raw emissions. There is always a trade-off between reducing NO\(_x\) and minimizing
particulates at the same time. EGR helps to reduce peak combustion temperature resulting in lower NO\textsubscript{X} emissions but as a drawback, particulates increase due to EGR [4]. Gasoline engines that are operated lean at part load are facing similar challenges as diesel engines. As a consequence of non-stoichiometric engine operation the 3-way catalyst will be insufficient to meet emission legislations. Therefore EGR is also needed for reducing raw emissions by using the same effect as in diesel engines.

Turbocharging an engine is a state of the art technology to reduce CO\textsubscript{2} emissions by utilizing the downsize effect [5]. Nowadays, the market share of turbocharged engines of passenger cars and light duty commercial vehicles is 34\% and will reach 43\% by 2019. Nearly all diesel engines in passenger cars are turbocharged and gasoline engines have followed this trend over the last years. The combination of turbocharging and EGR helps to fulfill the above-mentioned targets for reducing CO\textsubscript{2} and pollutants.

EGR can be realized internally with variable cam phasing or externally on the high pressure (HP) exhaust gas side before the turbine and on the low pressure (LP) side after the turbine of the turbocharger as shown in Figure 2.

![Figure 2: LP EGR and HP EGR concept for an internal combustion engine](image)

There are advantages and drawbacks for both concepts [6]. HP EGR is well proven. But it is only applicable in case of a sufficient pressure difference from exhaust to intake side. Hence, HP EGR will not be possible at low end torque with applied scavenging.

The driving pressure difference enables LP EGR for higher EGR rates. As LP EGR can be extracted after the catalyst or DPF it can be “cleaner” and does not require as high cooling capabilities because the temperature level at the intake of the EGR path is lower than for HP EGR. Moreover, the distribution of the EGR from cylinder-to-cylinder can be designed more equally.
Figure 3: EGR ranges for a gasoline engine with corresponding fuel economy benefits [8]

Figure 3 shows the potential application of HP EGR and LP EGR in the engine operational map of a gasoline engine including the corresponding fuel economy (FE) benefits.

External HP EGR applications are well known as they are in serial production for a long time. The first LP EGR application was introduced into the market for a diesel engine in 2008.

Beside the clear advantages of LP EGR applications, there are some side effects especially on the durability of the turbocharger compressor wheel. The exhaust gas which is mixed with fresh air upstream of the compressor inlet can contain particulates and condensed water. The liquid phase in the EGR flow can dissolve pollutants, which results in acids that cause corrosive attacks on surfaces. Based on previous investigations at BorgWarner a coating has successfully been developed to protect the compressor against particulates and corrosive attacks [7].

During the lifetime of an internal combustion engine with LP EGR the amount of water which is condensed out of the EGR can be very high. Main factors for condensation are the ambient temperature and humidity, the LP-EGR rate and the operating point of the engine. Internal BorgWarner studies on a gasoline engine show that condensation is not only a cold ambient or cold-start concern, it also occurs in steady-state
operation at standard conditions. It also shows that condensation of droplets under steady-state operation occurs mainly under low engine loads. Additional droplets can occur because of fog or spray which is sucked in by the intake pipe. Beside the droplets in the free stream, also a liquid wall film in the compressor inlet can occur, which causes different damage mechanisms. If droplets hit the rotating compressor wheel they have a strong erosive effect, which can cause severe damages, up to the total failure of the component. This is also well known at the blades of a helicopter under rainy conditions or in the last stage of a steam turbine. As seen in Figure 4, in general the impact speed, the cumulated water mass during the impact with droplets, the impact angle and the droplet diameter have the biggest influence on the destruction of the material [9].

Figure 4: Influence of droplet speed and water column (a), impact angle and duration of the impact (b) and droplet diameter and water column (c) on the depth of the erosion \( e_m \) [9]

The main factors for the impact velocity are the circumferential speed of the compressor wheel at the impact location and the velocity of the droplets upstream of the compressor inlet, relevant for the impact angle is also the shape of the blades. The main parameter for the erosion of water droplets is the normal component of the impact pressure, i.e. vertical droplets have the highest erosion. In [9] it is stated that in a rough esti-
mation, materials with high shear strength are mainly harmed by the normal component of the impact. Especially on ductile materials an annular shape zone around the impact shows wavelike deformation structures [9]. The deformation could be referred to strong tangential jets which are caused during the impact of the droplet. In [10] it is stated that these jets are caused by very large density and pressure differences across the droplet free surface (see Figure 5). The jets can reach speeds with a multiple of the impact velocity of the droplet and even higher than the speed of sound of the liquid phase.

![Diagram](image)

Figure 5: Intense lateral jetting due to the high pressure difference across the droplet free surface [10]

The main technical risks of erosion on the compressor blades caused by droplets are a reduction of the HCF properties, danger of blade cracking, decrease of compressor performance and possible changes of the rotor balancing. A change in the balance of the rotor also in combination with an eroded leading edge could lead to a change in the acoustic spectrum of the turbocharger. Also secondary damages e.g. by aluminum particles in the air path of an ICE have to be taken into account.

In this study the influence of water droplets on the spinning compressor wheel is investigated. To cover the main aspects a variation of the droplet size, the rotational speed, and the amount of water is investigated. The damage to the blade is studied and the impact on the thermodynamic parameters over time as well as on operational parameters like balancing, risk of failure, etc. is analysed. To ensure safe operation of the compressor wheel even under conditions where droplets can occur, one potential countermeasure is tested and presented in this study.
### 2 Test Setup and Method

Under real engine operation conditions liquid water from condensation in a LP EGR path may enter the turbocharger compressor in different forms, e.g. as wall film or as droplets with various droplet size distribution and flow rate. Which form of water admission is found on an engine is depending on the dominating formation mechanisms (accumulation and drag of wall film, droplet stripping at sharp corner, etc.) and therefore linked to the specific design of the LP EGR flow path and engine operation conditions.

In order to investigate the influence of the main parameters on the compressor deterioration the testing program has been defined as shown in Figure 6. Parameter variation 1 investigates the influence of the water admission type by subsequent tests with four different droplet diameters and one test with water admission via wall film. The cumulated amount of water as well as the compressor operation point was kept constant. Parameter variation 2 subsequently investigates the impact of the compressor speed, applying water droplets of constant diameter. In this phase, the amount of water has been increased to 20 l to additionally analyse the damage propagation with water admission time. The corresponding compressor operation points for variation 1 and 2 are highlighted in the compressor map in Figure 6.

![Figure 6: Configuration of the testing program](image)

For the admission of water droplets into the compressor inlet flow, a special droplet injector (see Figure 7) has been applied, which is able to generate a sequence of mono-disperse droplets, i.e. droplets with identical diameter. For the individual tests, the droplet diameter is adjusted by applying injector orifices with different diameters. The approach of mono-disperse droplets finally allows the correlation of compressor damage and droplet size.
The appropriate operation settings for the droplet generator (supply pressure and excitation frequency) along with the resulting parameters of droplet diameter \(d_{\text{Drop}}\), droplet frequency \(f_D\) (droplets per second) and flow rate \(\dot{Q}\) have firstly been derived in a laboratory. The generated droplet diameters have been determined by relative measurement with reference wires of known diameter (see Figure 7). The derived parameter sets for each orifice diameter is listed in Table 1.

Table 1: Parameter set for the droplet generator operation

<table>
<thead>
<tr>
<th>Orifice (µm)</th>
<th>500 µm</th>
<th>250 µm</th>
<th>150 µm</th>
<th>100 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply pressure</td>
<td>4 bar(a)</td>
<td>4 bar(a)</td>
<td>4 bar(a)</td>
<td>4 bar(a)</td>
</tr>
<tr>
<td>Droplet velocity (u_D) (abs)</td>
<td>24.5 m/s</td>
<td>24.5 m/s</td>
<td>24.5 m/s</td>
<td>24.5 m/s</td>
</tr>
<tr>
<td>Flow rate (\dot{Q})</td>
<td>11.3 l/h</td>
<td>3.2 l/h</td>
<td>1.26 l/h</td>
<td>0.54 l/h</td>
</tr>
<tr>
<td>Frequency (f_D)</td>
<td>9 kHz</td>
<td>18 kHz</td>
<td>20 kHz</td>
<td>45 kHz</td>
</tr>
<tr>
<td>Droplet diameter (d_{\text{Drop}})</td>
<td>1120 µm</td>
<td>470 µm</td>
<td>340 µm</td>
<td>153 µm</td>
</tr>
</tbody>
</table>

Droplet velocity \(u_D \approx c_{\text{air}}\) (at injection location)

The orifice diameters for the droplet generator have been chosen to cover a broad range of droplet diameters, representing different droplet formation processes like shear from wall film at sharp corners or secondary breakup into small droplets.

The testing setup for the investigation on the turbocharger testbench is illustrated in Figure 8. The droplet generator is positioned within the air
path upstream compressor, supported by a carrier tube. The mounting in the carrier tube allows tilting the droplet generator to achieve the desired spray targeting (see schematic). This setup additionally minimizes the relative velocity between droplets being injected and surrounding air flow to prevent secondary droplet breakup. A transparent pipe between the carrier tube and compressor inlet enables optical access to observe the injection process. The compressor operation point is controlled by a throttle valve mounted behind the measurement tube downstream of the compressor. The water injection process is started and stopped during the tests by a magnetic control valve, embedded into the testbench control.

**Testbench Setup**

**Spray arrangement**

![Image of testbench setup with labels](image)

Figure 8: Testing setup on the turbocharger testbench and spray targeting for droplet and wall film admission

The spray targeting for the direct admission of droplets onto the compressor blades is aimed at approximately 2/3 of the blade span in order to achieve a reasonably high blade velocity but to avoid wall contact of the droplets before entering the compressor. However, due to the turbulent nature of the inlet flow, along with the impact of the compressor rotation...
on the flow field upstream of the compressor, some scattering of the impact position on the compressor is observed. For wall film application, the droplet generator is targeted at the wall of the transparent pipe as depicted in the schematic drawing of Figure 8. The droplet generator configuration and parameters for the wall film test apply the setting with 250 µm orifice. The general boundary conditions for all tests are listed in Table 2. All tests were carried out with tap water to examine purely the effect of the droplet impact and to avoid superposition with other parameters such as corrosive media.

Table 2: Boundary conditions for the testbench investigation

<table>
<thead>
<tr>
<th>Test object and boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor type</td>
</tr>
<tr>
<td>Passenger car</td>
</tr>
<tr>
<td>Compressor diameter</td>
</tr>
<tr>
<td>47.5 mm</td>
</tr>
<tr>
<td>Number of blades</td>
</tr>
<tr>
<td>6 + 6 splitter blades</td>
</tr>
<tr>
<td>Injected medium</td>
</tr>
<tr>
<td>Tap water</td>
</tr>
<tr>
<td>No aggressive components</td>
</tr>
<tr>
<td>Oil supply</td>
</tr>
<tr>
<td>90 °C, 4 bar abs</td>
</tr>
<tr>
<td>Compressor inlet condition</td>
</tr>
<tr>
<td>Ambient</td>
</tr>
</tbody>
</table>

3 Testbench Investigation Results

The testing program listed in Figure 6 has been conducted on the FEV turbocharger testbench. Each of the separate tests has been performed with a new compressor sample in order to preserve and compare the damage levels.

3.1 Evaluation Approach

For the evaluation and assessment of the impact of water from LP EGR the following three criteria have been analyzed:

- Physical damage of the compressor impeller by visual inspection and SEM (scanning electron microscope) investigation
- Degradation of the compressor efficiency: continuous tracking of compressor efficiency and evaluation of the steady state compressor efficiency at regular operation (without water injection) before and after water injection
- Shifting of surge and choke limits of the compressor
3.2 Droplet Size Variation

On completion of parameter variation 1, i.e. variation of injected droplet size at constant TC speed, two different patterns of compressor blade damage have been observed, namely erosion of the leading edge and erosion of the blade surface. The blade erosion found on the leading edge of the impeller is compared in Figure 9 for the different droplet sizes.

The pictures show a significant increase of blade damage with droplet size. For the smallest droplets of 153 µm, only small deterioration of the leading edge surface is visible, while for the larger droplets a significant amount of material has been eroded from the leading edge. However, above 470 µm there is no further increase in blade damage visible, which indicates a saturated behavior of the damage impact with droplet size above 470 µm. The shape of the blade erosion gives no clear indication whether the dominant mechanism for the damage is the droplet impact itself or cavitation inside the impinging droplet. Additionally, it was observed that these damages were only found on the main blades. No damages were found on the leading edge of the splitter blades for any of the conducted tests.

Figure 9: Blade erosion of the leading edge found after droplet injection
The damage pattern found on the blade surface after droplet injection is illustrated in Figure 10. In contrast to the findings on the leading edge, the blade surface deterioration does not increase with droplet size, but rather with admission duration. Test sample #1 with largest droplet admission and shortest injection duration shows no surface erosion yet, though a discoloration in the outer span area is already visible. Test samples #2 and #3 show a similar level of surface erosion, which is mainly found on the outer span of the suction side. For sample #4 the main surface erosion is observed on the pressure side of the compressor blades.

In addition to the tests with droplet admission, also one test has been conducted with wall film admission to the compressor. For this test, the droplet generator configuration with 250 µm orifice has been applied since it represented the worst case configuration during droplet admission. The resulting impeller damage from this wall film test is shown in Figure 11 in comparison to the corresponding droplet admission results.

With wall film admission, the leading edge of the compressor wheel shows only marginal deterioration, mainly with some distance to the tip. The reason for this is the way in which the water enters the compressor. On the testbench it could be observed during water admission that the wall film was propagated towards the compressor as intended, but few millimeters before entering the compressor it was atomized by the compressor recirculation vortex at the leading edge tip. Thus, the water finally enters the compressor as droplets of very small diameter, causing accordingly small damage to the leading edge. However, the erosion on the blade surface observed here correlates well with the level found for droplet admission with the orifice of 250 µm.
To get more insight in the extent of the damage the compressor wheels have also been studied with a scanning electron microscopy (SEM). This analysis additionally helps to isolate the damage mechanism of the droplets. It showed that the damage on the leading edge is primarily caused by mechanical impacts while the amount of chemical processes (e.g. corrosion, etc.) is negligible. SEM images of the erosion on the leading edge are shown in Figure 12. Although it is more likely that the damage is caused by erosion the occurrence of cavitation could not completely be excluded as the damage is progressed too far. The detailed study showed that there are no micro-cracks in the blade structure that would indicate further cracking of parts of the blade.

Figure 11: Blade damage comparison between droplet injection and wall film admission; identical parameters for injection rate and test duration

Figure 12: Scanning electron microscopy analysis of the leading edge damage caused by droplets (#2) and wall film admission (#5)
Nevertheless, the erosion level observed on the compressor blades, especially at the leading edge with larger droplets, represents severe damage to the component, since it could affect the integrity of the mechanical structure if the impact with droplets would occur for a longer duration. In consequence, this could lead to secondary damages due to crack initiation and propagation or weakening of the HCF (high cycle fatigue) stability. Any debris or pieces breaking off the compressor are conducted towards the engine and could lead to further damages on the valves, cylinders and pistons.

A balance check after the test showed, that both the part balance and the balance of the complete rotor is still within the production limits.

Degradation of compressor efficiency:
Besides the physical damage of the compressor hardware also the degradation of compressor performance has been investigated. For this purpose, the compressor efficiency has been measured as reference under regular operation condition before start of water injection. During water injection itself, the instantaneous efficiency has been recorded continuously to observe the degradation process. After finishing of water injection, the steady state efficiency has been measured again to evaluate the change in performance in relation to the reference performance before water injection. Figure 13 exemplarily illustrates the performance evaluation in the left diagram. The phases before and after water injection are characterized by the settling of the steady state efficiency. These settling phases are used to evaluate the final efficiency drop $\Delta \eta_{\text{before/after}}$ caused by the damage due to water admission.

**Figure 13: Evaluation of efficiency degradation due to water admission**
The efficiency trace during water injection is characterized by a significant shift of the efficiency level. This does not reflect an actual increase of the thermodynamic efficiency, but is just an artificial effect caused by the injected water. Due to water vaporization the compressed air is being cooled, which finally leads to a higher calculated value for the efficiency. Since the ratio of vaporization is unknown and also unsteady, it is not possible to accurately account for this effect.

The right diagram in Figure 13 compares the evaluated efficiency drop for the conducted tests in relation to the droplet size. Interestingly, the highest efficiency change is not found for the larger droplets which caused the strongest damage to the compressor leading edge, but for the smallest droplets with an inversely proportional trend. This indicates that the efficiency drop is not dominated by the erosion of the leading edge, but rather correlates with the erosion found on the blade surfaces. This is additionally supported by the comparison of the wall film test (#5) with the corresponding droplet test (#2). Both tests exhibit the same level of efficiency drop, though the damage pattern of the leading edge is significantly different. Therefore, the dominating factor seems to be the surface erosion here. However, the overall observed efficiency drop is relatively small taking into account the severe damage found on the compressor wheel.

**Shift of surge and choke limits**

The third parameter that has been investigated in this study to quantify the effect of condensed water onto the turbocharger compressor is the change in operation range, i.e. the shift of surge and choke limits. For this investigation, the initial borders of the operation range have been scanned before start of water injection for each test sample. The choke limit has been defined here by compressor efficiency level of $\eta = 50\%$. After finishing water injection, both borders were scanned again and evaluated relative to the initial position. Figure 14 exemplarily shows the result for test #1 with largest droplets.

For the tests conducted within this study and the associated compressor damages no visible influence on the surge limit could be detected. The choke limit, in contrast, is increasingly shifted towards lower mass flow rate with larger damage on the leading edge of the compressor. The largest shift of approximately -3 % is found with deepest erosion of the leading edge, while for the minimal erosion level with small droplets the choke limit is practically unaffected.
Figure 14: Effect of water admission onto the compressor surge and choke limits

There are two reasons for the different impacts of the damage on surge and choke limits. The first is the difference in the dominating impeller zone for the two aspects. While the choke limit is mainly affected by the flow field, or specifically Mach number, at the impeller inlet, the onset of surge origins rather from flow separation at the trailing edge. The second reason is the difference in relative velocity of the flow field to the impeller. Due to high relative velocity at choke limit the deterioration of the leading edge causes a strong generation of turbulence and with the disturbed flow field a restriction of flow cross section. At surge limit, the relative velocity is rather low, which causes only small disturbances of the flow field with blade damage and consequently leaves the surge limit almost unaffected.

3.3 TC Speed Variation

From the results of parameter variation 1, i.e. droplet size variation, it has been seen that the biggest damage to the compressor wheel was reached with the droplet generator orifice of 250 µm and corresponding droplet diameter of 470 µm. For this reason the subsequent variation of compressor speed has also been conducted with this droplet generator configuration, representing the worst case condition. The investigated compressor speeds ranging from 50 krpm to 200 krpm have been selected to cover the full operating range of the turbocharger occurring under engine operating conditions. Figure 15 compares the level of the blade erosion found for the speed variation as well as the measured efficiency drop caused by the compressor wheel damage.
As expected, the compressor speed or more precisely the related impingement velocity of the droplet has a significant impact on the blade erosion. While for the lowest speed of 50 krpm there is no wear of the compressor wheel visible yet, the sample of the 100 krpm test exhibits very small initial impingement marks on the leading edge. With 150 krpm the damage level increases drastically and the largest erosion is finally found with highest compressor speed (200 krpm) though the difference to 150 krpm is relatively small.

The development of the blade damage over compressor speed is also reflected in the efficiency drop plotted in the right diagram, but similar to the findings of parameter variation 1, the efficiency deterioration is relatively small in relation to the observed damage level.

In addition to these observations, comparing the result at 150 krpm with the corresponding test #2 of droplet size variation gives further information about the propagation of erosion. Despite the large increase of the injected amount of water (from 5 to 20 l), the damage level of the 150 krpm sample closely resembles the results of test #2. This indicates that the erosion level is not propagating continuously, but seems to reach a certain saturation level. A probable explanation for this could be a stronger deflection of the droplets from the leading edge due to a disturbed flow field induced by the roughened surface.

Summarizing, the results of the speed variation indicate that there is a critical speed in the range of 100 krpm or correspondingly 250 m/s circumferential speed, below which the damage potential of water droplets is
very small. Above this speed, a rapid increase of the compressor wheel damage is to be expected with water admission. Unfortunately, limiting LP EGR application to operation regions where compressor speed is below this critical speed is not sufficient to effectively prevent damage. Under real engine conditions there will always be a considerable delay between condensation of water in the LP EGR loop and the actual admission of this water to the compressor. With transient engine operation it is very likely that the turbocharger reaches speeds with high damage potential until condensed water reaches the compressor. Therefore, additional measures need to be applied to reliably protect the turbocharger hardware on engines with a LP EGR system.

### 3.4 Compressor Coating

As a final step of this study and as an outlook, one additional test has been carried out with a coated compressor wheel, representing one potential measure to protect the compressor under water admission conditions. In order to derive conclusive proof of the functionality of the coating it was tested under worst case conditions taken from the previous test, i.e. droplet diameter of 470 µm, 200 krpm compressor speed and cumulated admission of 20 l of water. The results of this test in comparison to the corresponding test with non-coated compressor are shown in Figure 16.

![Uncoated compressor; 200 krpm](image1)

![Coated compressor; 200 krpm](image2)

![Figure 16: Comparison of the blade damage and efficiency drop for a coated and a non-coated compressor; droplet size $d_{\text{Drop}} = 470 \mu m$, 200 krpm TC speed, 20 l water injected](image3)

From the pictures on the left side it can clearly be seen, that the coating effectively protects the compressor hardware from erosion due to water droplet impingement in this test. While the uncoated compressor is severely damaged after the test, the blade surfaces and blade leading edges of the coated compressor do not show any visible deterioration or erosion.
Correspondingly, also the efficiency drop found with the uncoated compressor was eliminated completely with the coated compressor. No change was measurable in the performance before and after water injection.

Of course, this test result with a coated compressor needs to be understood as a first step. Further investigations are required to validate its functionality also under real engine and EGR condensation conditions especially with regards to durability and lifetime. Nevertheless, the comparison of coated and non-coated compressor is a very promising result for future application of compressor coating on engines with LP EGR System.

4 Summary and Outlook

Future emission legislations will lead to an increasing number of LP EGR applications. The challenges connected with mixing exhaust gas and fresh air upstream of the compressor affects the turbocharger in many aspects. The focus of this study was to identify the influence of water droplets hitting the spinning compressor wheel. Variations in the type of water admission, droplet size and wall film, as well as a variation in the compressor speed have been conducted. Increasing droplet diameter showed an effect by physical damage of the leading edge, but the decrease in efficiency rather correlated to the surface damage of the blades. This was additionally supported by a test with wall film admission with a completely different form of damage but the same drop in efficiency, applying the same amount of water and test time. A variation in the rotational speed of the compressor showed the expected dependency between the impact speed and the occurring damage respectively decrease in efficiency. Below a critical rotational speed of approximately 100 krpm no effect is measurable. For all other cases the overall drop in efficiency is measurable, but on a low level in relation to the visible damage. It will most probably not be perceivable for the vehicle driver to realize a starting damage. Although noise has not been investigated here, it is likely to increase and rather noticeable as a damage indicator. The operating range of the compressor stage is only affected with regards to a lower choke limit which could have a slight impact on rated power or reduction of high altitude margin.

Further to the impacts on performance, the most important aspect is the physical damage of the impeller and especially the associated risk of follow up damage to the compressor and the complete engine.
With this study the broad basis for further investigations is made. For a potential future solution to protect the wheel against erosion due to water droplets a compressor coating has been tested with very promising results. The blades showed no erosion, neither on the leading edge nor on the surface and also there was no measurable performance degradation of the compressor. To prove that this could be a potential solution for series application further validation especially with regard to durability and life time need to be performed.

References


http://www.3k-warner.de/de/press/knowledgeLibrary.aspx
Retrieved: 10.7.2014


