

Eliminating Engine Performance Degradation Over Time Through Compressor Redesign

Eric Krivitzky
 Concepts NREC

Masashi Yamamoto
 Mitsubishi FUSO Truck and Bus Corp.

ABSTRACT

Commercially available turbocharged internal combustion engines require robust system performance to maintain driveline power output capability. As in-service runtime increases, the accumulation of wear or deposits can adversely affect component performance levels. In a worst-case scenario, the component performance degradation leads to a vicious loop of declining system performance. Endurance testing of a heavy-duty diesel engine revealed performance deterioration over time. Oil deposits, resulting from oil mist associated with the closed crankcase ventilation loop, were observed on the turbocharger compressor and were tied to the deterioration. Cleaning of the compressor recovered initial performance for a short period of time. A different model of turbocharger, when substituted for the original, did not show the same degradation in output. This paper presents a study into the responsible mechanisms for performance deterioration and the compressor redesign that successfully avoided these issues. The results of numerical and physical investigations aimed at mitigating the system impact are discussed, starting with an overview of the observed engine and compressor performance decline, and an outline of potential areas of performance sensitivity to oil accumulation. Ultimately, the degradation of system performance was tied to the system response of deteriorating compressor characteristics. A compressor was redesigned and endurance tested to verify that the adjustment of engine-compressor matching and compressor characteristics results in improved robustness to oil-mist related performance degradation.

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INTRODUCTION

Diesel engines in the heavy-duty on-highway market are expected to perform consistently over extended maintenance and overhaul schedules. Minor deterioration in performance may be expected prior to engine overhaul, due to component wear and accumulated deposits, but significant degradation in power output or fuel economy over short periods of time is highly undesirable in a competitive market. Mitsubishi FUSO was experiencing such a scenario with one particular engine configuration. Engine durability testing revealed a reduction in turbocharger performance after relatively short runtimes. [Figure 1](#) indicates the boost pressure as a function of endurance test time. The test approach implemented engine controls to maintain a constant engine torque. As compressor pressure rise deteriorated, the system responded with an increase in exhaust gas temperature. In-field testing confirmed test-stand expectations of reduced engine power output. The deterioration of performance was linked directly

back to the ingestion of oil particles in the crankcase ventilation flow. If the crankcase vent was opened to atmosphere (OCV), rather than looped back to the engine inlet (CCV), the performance deterioration ceased.

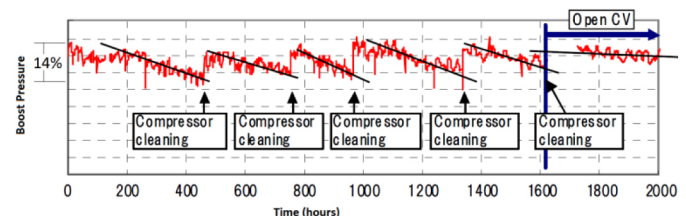


Figure 1. Boost pressure degradation over time on the engine endurance test stand. Cleaning of the compressor hardware returns performance back to initial levels.

Regulations on total engine emissions include both exhaust and crankcase discharge, and since crankcase blow-by is heavily oil laden, an OCV solution is only viable with

sufficient filtration. Many engines rely on the CCV configuration to handle crankcase blow-by. Ideally, the CCV flow is delivered back to the inlet relatively clean, to minimize the potential for deposits and fouling of the inlet components, including the turbocharger and the downstream loading on the aftertreatment system. However, even with in-line filtration of the CCV loop, small oil droplets on the order of 1 micron and below are still present in the CCV flow that is reintroduced to the incoming fresh charge.

Disassembling the turbocharger after a few hundred hours of operation revealed a significant amount of oil accumulation on the compressor impeller, casing, diffuser, and volute walls, as indicated in [Figure 2](#). A thorough cleaning of the compressor components returns the performance to as-new condition for a small period of time (results shown in [Figure 1](#)).



Figure 2. Oil buildup on the compressor's stationary and rotating walls.

During the endurance test cycle, a second turbocharger model was fitted to the engine. This turbocharger, denoted 'B' herein, did not exhibit the same degradation in performance when subjected to the same environment as turbocharger 'A'. In fact, the performance with and without CCV was essentially identical, as shown in [Figure 3](#). Unfortunately, the reality of the situation was that turbocharger A provided higher performance levels and possessed additional traits, such that it was greatly preferred over turbocharger B. Oil accumulations were also observed in compressor B ([Figure 4](#)), however, the distribution of accumulation on the impeller was different than seen on compressor A.

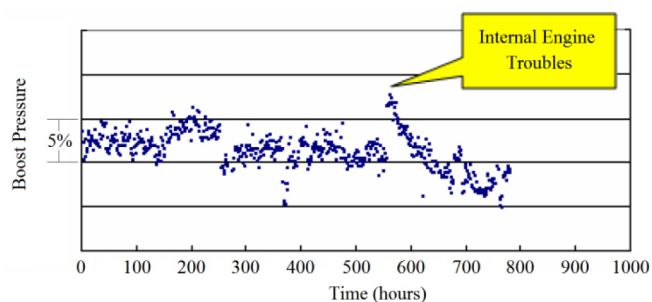


Figure 3. Compressor B performance does not degrade with time, even in the CCV configuration.

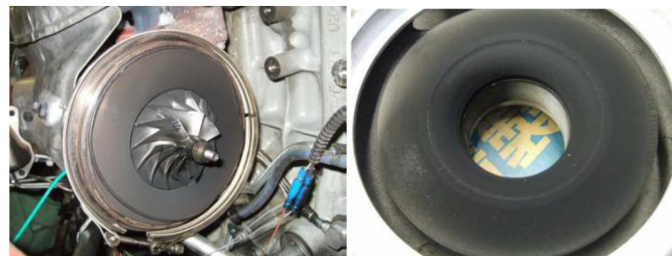


Figure 4. Compressor B oil accumulation is similar to Compressor A on the stationary components.

A wide net was cast, as shown in [Figure 5](#), to understand the fundamental mechanisms and address the problem at its source. This paper will cover much of the investigational work and ultimate resolution for boost deterioration from a compressor standpoint, focusing on why compressor A was sensitive to CCV while compressor B was not. The change from compressor A to compressor B represented the only change capable of stemming the boost pressure deterioration without violating the emissions targets via an open crankcase vent. Starting with a comparison of the two compressors, a geometrical analysis will serve to highlight the fundamental differences in the underlying design philosophies, while a comparison of the performance map, oil accumulation regions, and the resulting engine match will indicate operability differences. The discussion will then cover various potential sources of degradation that were identified, including a summary of the suspected source of degradation. A new compressor design, aimed at verifying the final hypothesis, is outlined with test-stand results verifying the approach.

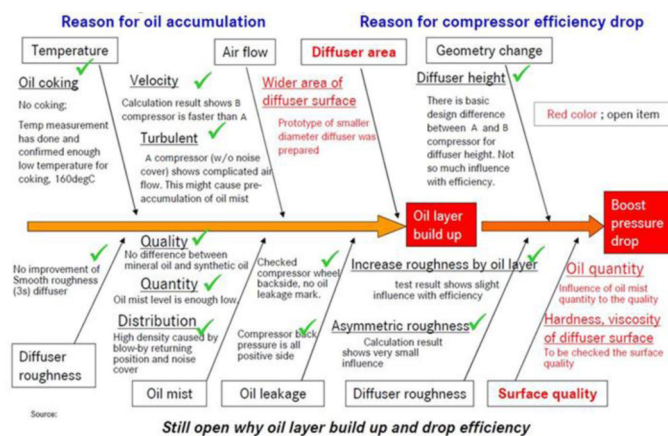


Figure 5. Outline of the upper-level potential sources for oil deposits and efficiency degradation.

COMPARISON OF THE TWO COMPRESSORS

Oil Mist Accumulation

As mentioned previously, the CCV oil mist resulted in an oil deposit on the stationary and bladed surfaces. Both turbochargers experienced oil deposits along the shroud and on both walls of the diffuser, with similar levels of coverage, visual depth, consistency, and estimated roughness. However, the impellers exhibited markedly different deposition patterns, as illustrated in [Figures 6](#) and [7](#). Blow-by is generally composed of a range of oil droplet sizes, measuring from ~ 20 micrometers down to 0.1 micrometers or finer. The range of droplet sizes is subdivided by the primary methods of deposition, namely: large droplets ($>1 \mu\text{m}$) have significant enough inertia, so they are unable to follow changes in flow direction, resulting in inertial deposition. Medium-sized droplets ($0.1\text{--}1.0 \mu\text{m}$) have reduced inertia, which enables flow-field following and entrainment within recirculation regions, but are large enough to enable viscous boundary layer effects to slow and trap the particles. The smallest-sized droplets ($<0.1 \mu\text{m}$) have sufficiently low inertia and their deposition relies on Brownian motion (Wenglarz [1]). Due to the very nature of the various droplet sizes, the CCV flow introduced into the inlet is comprised primarily of particles $<1 \mu\text{m}$, as revealed via measurements made before and after application of a blow-by filter. The filter is quite effective at removing the larger particles, but a significant amount of smaller particles ($<0.4 \mu\text{m}$) remain. As a result of this particle distribution, containing significant content that follows the flow, the oil deposit patterns can shed light on the underlying flow field character at the time of deposition.

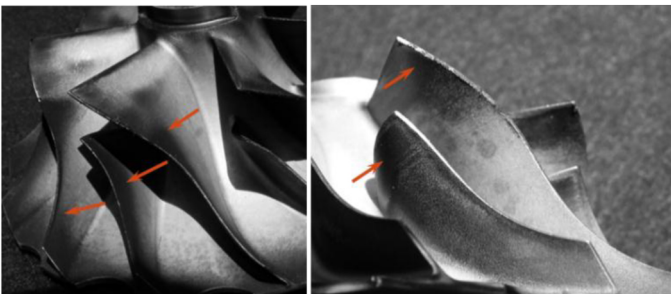


Figure 6. Compressor A impeller oil deposit regions suggest high-incidence or near-surge operation.

Careful examination of [Figure 6](#), showing the oil deposits on compressor A before installation of the blow-by filter, reveal deposition that is consistent with operation under high-incidence, or near-stall conditions. Two specific oily areas suggest this conclusion: there are significant deposits on the pressure side of the leading edge, while the suction side remains relatively clean. Further along the passage, a region of oil is observed that spans the passage and then appears to migrate towards the tip. The pressure side deposits are likely

inertial in nature, while the flow may be separating off the suction side of the leading edge, resulting in the relatively clean section of blading and the creation of a secondary flow region that migrates towards the shroud as it combines with the tip clearance flow (as depicted in [Figure 8](#)).

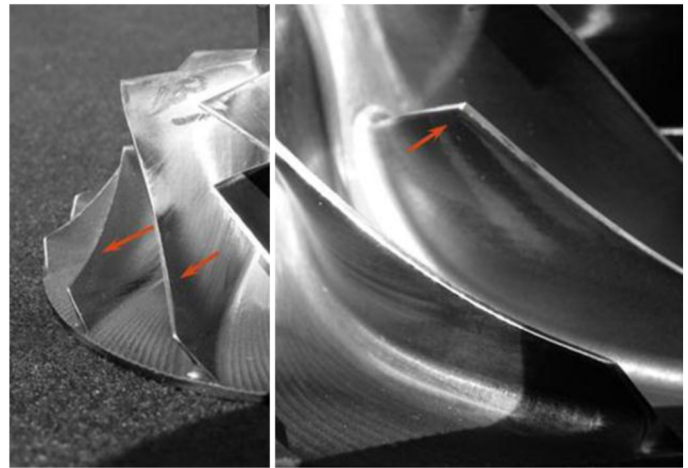


Figure 7. Compressor B impeller oil deposit regions indicate a relatively benign compressor operating point.



Figure 8. A sketch showing the likely secondary flow field effects contributing to oil deposits within compressor A, operating at high incidence.

Close examination of [Figure 7](#), showing oil deposits on compressor B before installation of the blow-by filter, suggests minimal recirculation within the flow field and relatively benign incidence. The oil accumulation along the blade tip in the exducer region is consistent with traditional regions of low-momentum fluid found in this class of compressor, even at peak efficiency. Some accumulation is noted along the pressure side of the splitter blade, and this may be the result of negative incidence on the splitter itself or