

Procedure for Determining the Allowable Particle Contamination for Diesel Fuel Injection Equipment (FIE)

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ABSTRACT

Increasing injection pressures together with Diesel fuel lubricated Common Rail pumps replacing oil lubricated systems demand a more sophisticated investigation of robustness and durability against particle contamination of fuel. The established way of requiring filtration efficiency levels per lab standard is not significant enough if we look at variable factors like vibration of the fuel filter and viscosity of the fuel. Because these and other factors tremendously influence filtration efficiency, future Diesel FIE cleanliness requirements will need to define an allowable contamination limit downstream of the filter. More precisely, this is not a scalar limit but a contamination collective that considers the varying vehicle filtration and operating environment.

This paper describes a procedure for defining allowable contamination limits of the FIE components. The procedure includes sensitivity, robustness and "key life" tests. The latter one is similar to a S-N curve (Woehler curve) and is the basis for the damage accumulation model of particle contamination.

INTRODUCTION

Emissions legislation is getting more and more stringent for all major Diesel markets in the world. Fig. 1 refers to emission regulation levels expected in 2015.

One measure to reach these emissions goals is an increase of the fuel injection pressure. Systems with pressures up to 2500 bar are already available and will get more and more common from 2011 onwards. Doubling of injection pressure since introduction of Common Rail systems in the 1990s has led to a higher demand on the precision of all machine elements of the FIE. Fuel quality in general and particle contamination in particular is more important than before.

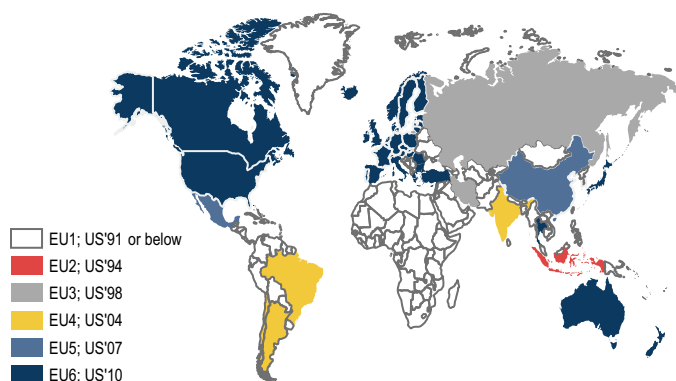


Fig. 1: heavy duty truck emissions legislation 2015 [1]

The established standards (SAE J1985 and ISO 13353 replaced by ISO 19438) for determining the filtration efficiency apply a constant flow rate, a relatively coarse test dust and in case of the ISO standards a test fluid with viscosity 5 times higher than Diesel. This means these standards do not represent the respective

conditions in the vehicle which influence filtration efficiency. Furthermore, they do not address the considerable effect of vibration [2]. Adaptation of the standards is presently under discussion, but the result cannot be foreseen at the moment. Therefore, the previously used technique of fuel filter selection based mainly on the standards mentioned above is not sufficient to ensure trouble-free operation in the field.

Contamination specifications in most Diesel fuel standards worldwide limit only the mass of contamination. These mass limits allow a huge amount of small particles that is not acceptable for the FIE. The Worldwide Fuel Charter of major automotive and engine manufacturers associations [3] was the first to propose limits of particle contamination per ISO 4406 for fuels. For hydraulic power systems this has been common practice for a long time. It was first expanded to a fuel standard in 2008 (UK military standard of kerosene, DEF STAN 91-91 Issue 6).

Experience in particle critical markets and applications confirm the need to limit the particle contamination level entering modern high pressure FIE. In the future, Bosch plans on specifying an allowable particle contamination of the fuel per ISO 4406 at FIE inlet instead of a filtration efficiency. This allowable contamination limit is derived by comparing the robustness (strength) with the load. The following describes the procedure of adjusting load and strength regarding particles and defining load limits (allowable particle contamination per ISO 4406). After describing the effect of fuel-borne particles on a typical FIE, the next step is to determine the relevant loads and operating conditions. The strength is then assessed and the allowable contamination limit is derived.

IMPACT OF PARTICLES ON DIESEL FIE

This section discusses in detail how particles harm a FIE. The investigations are exemplified on a Common Rail system that is widely used in many regions of the world.

DAMAGE MECHANISM AND FUNCTIONAL IMPACT

The main impact of particles on the FIE is found on the injector. Fig. 2 shows a BOSCH injector CRI2. Typical for this injector type is the ball-seated control valve.

The control valve separates the region of the injector with rail pressure (up to 1600 bar) from the low-pressure backflow (approx. 1 bar). Actuating the control valve initiates the injection [4].

The main functional impact of particle contaminated fuel is a large injector leakage increase to the backflow, see Fig. 3. Because of the increased backflow, the high

pressure pump cannot deliver the necessary quantity to meet the commanded rail pressure. This can lead to a control unit command to shut-down the system. Typically this occurs during engine cranking. Starting problems are representative of an injection system damaged by particle erosion.

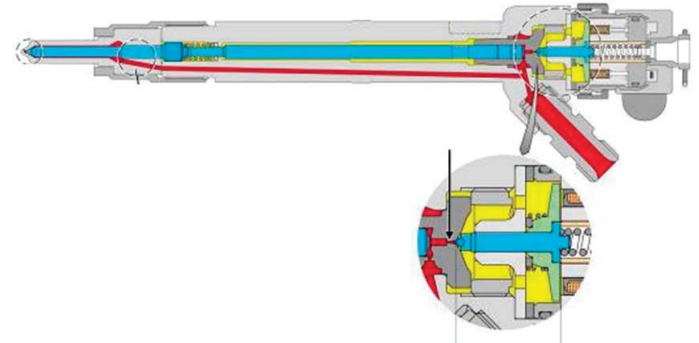


Fig. 2: BOSCH CRI2 injector with control valve detail view; red: high pressure area, yellow: low pressure in the backflow

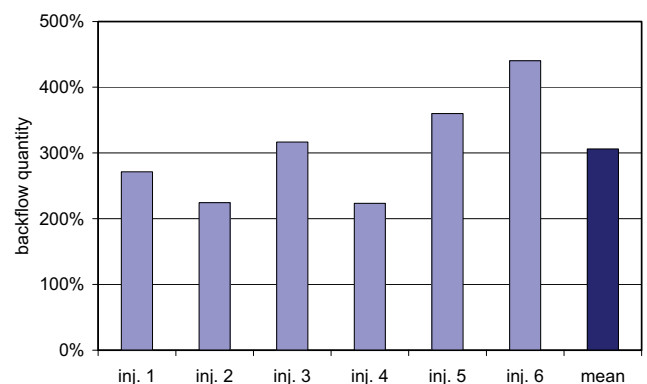


Fig. 3: injector backflow quantity increase caused by particle impact (set point at 1600 bar / 900 μ s); 100 % indicates the backflow before test

The visual inspection of a damaged injector in Fig. 4 shows severe erosion traces in the ball seat of the injector valve.

A detailed analysis reveals different phases of the damaging process: in the first phase single scratches can be observed. Later, several of these scratches connect to small channels as can be seen on the upper right side of Fig. 4. Once these channels are formed, the valve no longer seals adequately, the leakage increases significantly and leads to additional erosion. This self-energizing phase can be monitored by an increase of the backflow rate. Finally, a huge channel is formed (seen on the lower left side of Fig. 4) and causes injector malfunction.

Another functional impact is an increase of the injection quantity as shown in Fig. 5. This can lead to black smoke in the exhaust gas. This effect is gradual, and is therefore not as easily detected as the sudden effect of not starting or stalling of the engine. Therefore we focus on the failure mode “backflow increase”.

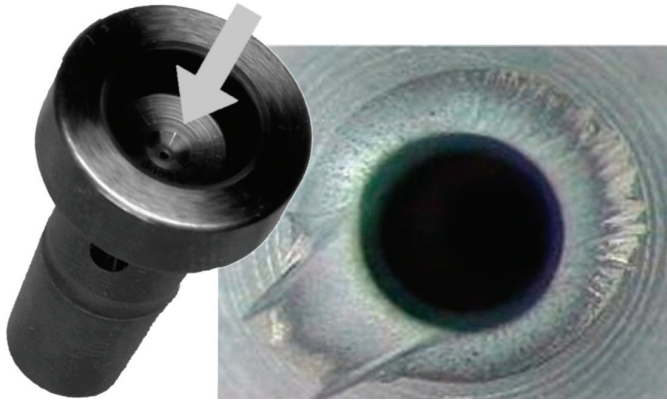


Fig. 4: ball valve seat of injector CRI2, eroded by particles in the fuel

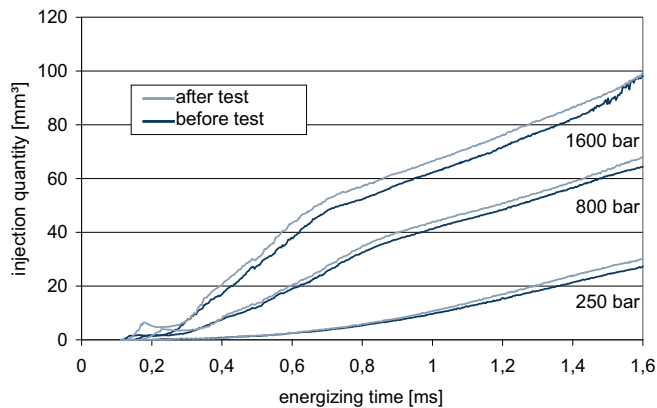


Fig. 5: injection quantity map before and after test with dust contaminated fuel

LOADS REGARDING PARTICLE EROSION

To design a test which targets a special failure mechanism, it is necessary to know the critical load factors for this mechanism. Investigations have revealed particle size, particle hardness, particle concentration and flow at the machine element as being essential.

Particle size

The influence of particle size on the damage mechanism was investigated. An example particle size distribution downstream of a fuel filter is shown in Fig. 6. Four different narrow band test dust size distributions were used which cover the range downstream of a fuel filter. The size indicated in Fig. 7 represents the mean size of the test dusts determined by a Coulter Counter.

Fig. 7 shows the runtime until end of life for different particle sizes at constant particle concentration (number of particles per ml). Each data point represents the median of a set of 6 injectors and therefore demonstrates a high significance of the test. Further data is given in section “Test reproducibility” below. In the considered range of particle sizes a doubling of size leads to a reduction of lifetime of one order of magnitude! This demonstrates the need for specifying size dependant particle limits instead of total particle mass or a uniform contamination limit.

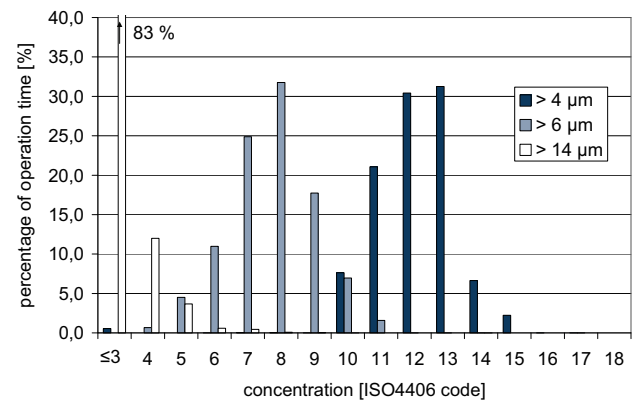


Fig. 6: average particle concentration downstream of the filter, various driving conditions, passenger car, Europe

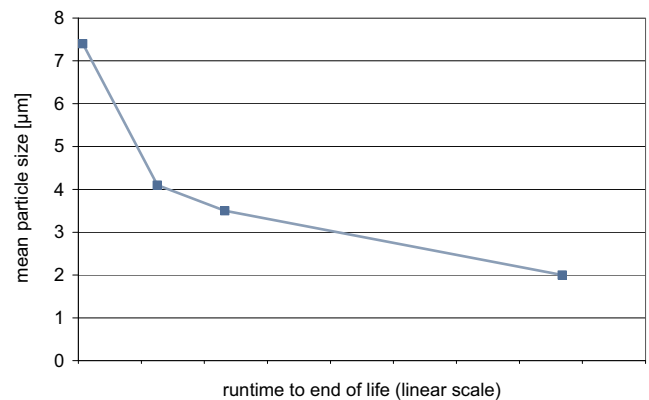


Fig. 7: impact of different particle sizes on lifetime at constant particle concentration

Furthermore it clearly indicates that filtration efficiency parameter β should be assessed dependent on particle size and not as aggregate for appropriate filter selection. However, for simplification of the diagrams most of the presented results are focused on the size $>4 \mu\text{m}$.

Particle hardness

Particle hardness also has a strong influence on FIE lifetime. The inorganic materials SiO_2 , Al_2O_3 and Fe_2O_3 are typically identified in analyzes of particles. Particles from these materials and their relative quantity have the main impact, due to their high hardness. Hardness values for these materials are shown in Table 1. Thus, this impact must be taken into account by using a test dust with a field-relevant particle material distribution.

Flow

Particle flow through the valve is given by the design and operating conditions. Operating conditions are injection duration, rail pressure and the total number of injection cycles. An increase of any of these parameters can lead to greater valve damage. The operating Conditions are defined by the OEM engine application and the mission profile for the specific vehicle or equipment. Representative application parameters and simulated usage profiles are used for the FIE particulate contamination evaluations.

	material of inorganic particles		
	Al_2O_3	SiO_2	Fe_2O_3
Mohs hardness	9	7	5-6
Vickers hardness	≈ 2000	≈ 1100	≈ 700

Table 1: hardness of inorganic materials that appear in particles [5]

Particle concentration

Last but not least, the particle concentration (size dependant number of particles per ml of fuel) has a strong impact. The following section discusses this in detail.

PARTICLE LOADS TO THE FIE

Two main topics are discussed – where do the particles come from, and what influences onboard filtration in the vehicle?

PARTICLE SOURCES

The source that comes first into mind is the particle content of fuel received from fuel station dispensers. Fig. 8 shows a summary of contamination per ISO 4406 coding from 2006 SGS fuel surveys of Europe, the U.S. and China for mineral Diesel and biodiesel blends (up to maximum B5 blend level).

In the U.S. and in Europe (European Union of the 12 countries 1986 – 1995) an average ISO code of 18 for the lowest size class $>4\mu\text{m(c)}$ was observed. For China, the average shifted to higher contamination values by at least 2 ISO code classes. This represents at least 4 times higher particle numbers on an average base. Also, the distribution range in China is broader and there are few fuel stations sampled with a very low contamination compared to those with higher contamination levels.

Field experience has shown the mean value of the ISO classes observed in samples taken from fuel station dispensers (ex fuel station) is not a proper method to assess the criticality of particle contamination in a fuel market. Using the 80th percentile of the $4\mu\text{m(c)}$ ISO classes proved to be appropriate to classify a market's fuel cleanliness ex fuel station. Fig. 9 groups the world based on the following classification: markets with an 80th percentile of the $4\mu\text{m(c)}$ class with maximum 19

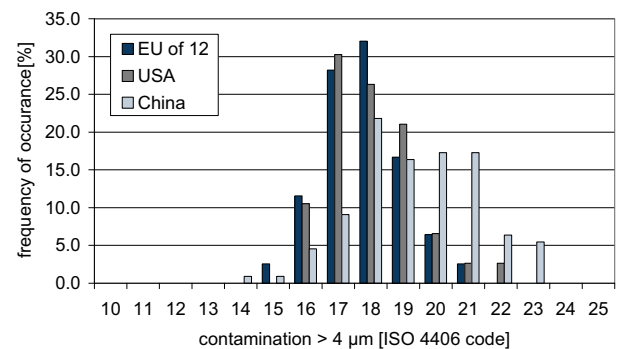


Fig. 8: particle contamination of Diesel fuel (ex fuel station) based on SGS worldwide fuel survey 2006

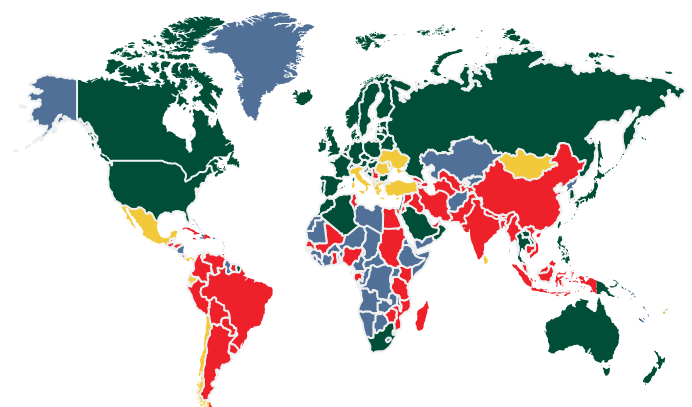


Fig. 9: particle contamination of Diesel fuel ex fuel station: 80th percentile ($>4\mu\text{m(c)}$ per ISO 4406) of ≤ 19 (green), $=20$ (yellow), ≥ 21 (red); based on SGS fuel surveys 2004-2007