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OPERATING PROBLEMS OF TURBOCHARGING SYSTEMS IN COMPRESSION-IGNITION ENGINES

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Abstract

Supercharging of diesel engines is one of the most popular methods of improvement of their operating indexes by influencing their general efficiency, volumetric and mass power coefficient (downsizing), unit exhaust emissions etc. Turbocharging systems are commonly used in compression-ignition engines and spark ignition engines. The most common type of supercharging is turbocharging based on a turbocharger as the main element.

It is a flow machine, in which a turbine rotor and compressor rotor are found on the common shaft. The turbine rotor is propelled with the exhaust gas from the engine while the intake air flows through the compressor rotor. The use of a turbocharger allows utilization of waste energy of the exhaust gas for improvement of parameters of the air supplied to the cylinders from the point of view of fuel combustion (increase of density and turbulence degree).

Due to unfavorable operating conditions such as high temperature of the exhaust gas (for compression-ignition engines – up to approx. 800 ºC and for spark ignition engines – up to approx. 1100 ºC), very high rotational speed (up to approx. 250 000 rpm), precise structure and complex encapsulation, a turbocharger is particularly exposed to damage or failures.

The operating problems of contemporary diesel engine turbocharging systems as discussed in this paper, relating to turbochargers and deriving from research and expert practice of the authors, constitute conclusions of the activities to some extent, which may contribute to further works on the improvement of diesel engine charging systems. This paper presents four types of damage occurring in turbochargers as divided into their causes. According to the division assumed in this paper, the damage is caused by:

- inappropriate lubrication,
- presence of foreign objects,
- exceeding the admissible rotational speed of the turbocharger shaft or excessive pressure and exhaust gas temperature,
- corrosion.

This paper addresses each of the above-mentioned cases and describes causes and effects of the same.

Keywords: *compression-ignition engines, damage, turbocharger, turbocharging*

1.Introduction

Engine charging involves feeding fresh charge of increased density into the engine cylinders, which enables feeding greater fuel mass (without changing the λ air excess coefficient). Charging aims at increasing of the unit power, efficiency and decreasing the unit exhaust emissions [3]. The increase of the charge density is obtained with an external machine (compressor) or the use of dynamic properties of the engine itself. The improvement of charging (which considerably improves the engine efficiency), consistent with the improvement of the power energy balance, is based on the increase of the turbocharger output in a wide range of revolutions and taking into account of the engine properties and a reduction of the turbine inertia.

Thus, the evolution of charging systems leads to the improvement of the turbocharger efficiency and opportunities to control the charging pressure regardless of the engine operating conditions. Making a compressor drive independent of the engine parameters makes it possible to precisely control the charging pressure.

Initially, mainly turbochargers fitted with a wastegate were used in direct injected compression-ignition engines, which were later replaced by variable geometry turbochargers. Turbocharging in high-volume vehicle production was first applied in the early 60s in a GM Chevrolet Corvair. Unfortunately, the vehicle was characterized by poor operating indexes during operation at low speed ranges– its turbocharger was highly inertial, which generated a 'turbolag', which made smooth driving impossible.

A "turbolag" was the biggest problem in early turbocharged engines and discouraged drivers from using such solutions. Despite the fact that turbocharged engines were used successfully during car races (BMW 2002 F1 formula), passenger cars always required a more evenly distributed supply of power. Turbochargers of that period were large and heavy and began to rotate only at the shaft revolutions of 3500 rpm and their power for low speeds was rather low.

In 1975 Porsche was the first company to manufacture the first turbocharged vehicle operating in a different way. It was Porsche 911 Turbo 3.0 with a mechanism allowing a turbocharger to gain speed before the supercharging actually began. The essence of this mechanism was a recirculation pipe and a valve that started exhaust gas recirculation before the exhaust gas generated adequate pressure for the operation of a turbine. Therefore, the 'turbolag' was much shorter and its power increment was more linear.

Three years later, Porsche manufactured a 911 Turbo with 3.3 l engine, which followed the 911 Turbo of 1975. The vehicle was equipped with a intercooler.

Development of charging systems aims at the improvement of the efficiency of turbochargers and the opportunities to control the charging pressure regardless of the engine operating conditions. Making a compressor drive independent of the engine parameters makes it possible to precisely control the charging pressure. Electrically driven compressors are a possibility in the future. Apart from precise control, their additional strong point involves an opportunity to increase the efficiency of the exhaust gas aftertreatment systems by eliminating of a turbine causing a decrease in the temperature of the exhaust gas directed to the aftertreatment systems (NO_x and Pm in particular). A technological and structural improvement (including the improvement of the inertia parameters) could be achieved by a decrease of the weight of the turbine and compressor rotors. An overview of modern charging system solutions is widely described in the subject literature.

A turbocharger is propelled with exhaust gas and its task is to pump the largest possible volume of air into the cylinders. It is placed in the exhaust manifold as close as possible to the exhaust gas inlet to the manifold so as not to lose the kinetic energy of the exhaust gas for the passage in the exhaust system. Exhaust gas passing with high speed drives the turbine rotor connected with the compressor rotor by a common shaft. Air is sucked mostly by a cone filter and gets straight into the inlet manifold after compression. The turbine rotor rotates with the speed reaching 290 000 rpm. The exhaust gas of the temperature of $900^{o}C$ and the high rotating speed cause the turbocharger to heat up to very high temperatures. Such extreme operating conditions are very demanding.

A turbocharger has to be precisely manufactured from materials of the highest quality. It consists of an exhaust gas driven turbine and a compressor mounted on the opposite ends of a common shaft and closed in a cast shroud.

An exhaust gas turbine has a turbine wheel and a shroud with an inlet and outlet cast of high-cadmium alloys or heat-resistant alloys based on cobalt and cast with the use of the lost cast waxing technology. An air compressor is composed of a cast compressor wheel and the shroud. Both sections are mounted on the opposite ends of a common shaft and closed in a cast central body of the turbocharger.

A shaft connecting two sections is embedded with the use of a carefully designed system of bearings for obtaining high rotational speeds and, unlike the crankshaft bearings, for small loads. They have to maintain the turbine and compressor wheels in the smallest possible distance from the shroud. The main tool in keeping their position is the space filled with oil found between the shroud, the bearings and the shaft. They have a decisive influence on the efficiency and durability of the turbocharger.

Sealing systems separate the shroud from the turbine and compressor sections. They prevent oil from passing to the operating area of the turbine and compressor and from passing of the exhaust gas to the central area of the turbocharger.

The applied engine oil has to be of top quality. Following the start of the engine and before driving, the engine should reach the operating temperature of approx. 90^{o}C in order to ensure minimum appropriate conditions for lubrication of the turbocharger bearings. The same rule applies when the engine is stopped. Modern vehicles are equipped with a turbo timer preventing immediate engine stop after high-speed driving and showing the time left for the turbine to cool.

One of the basic signals of a failure of the turbocharger is a decrease in the engine power and increased noise during engine operation. Another syndrome of turbine wear is tailpipe smoke. Blue exhaust gas may indicate that engine oil is burnt, which may be caused by a loss of airtightness of the turbine, whereas black exhaust gas may indicate that some fuel remains unburnt and the turbine pumps too little air. There are many reasons for smoke appearance (failure of the injection pump or injectors). Therefore, not every smoke appearance signifies a failure of the turbocharger. A turbocharger failure may also lead to engine overload, which is at best indicated by a light on the instrument cluster and, in extreme cases, may lead to engine damage [1].

Despite the fact that turbochargers are precision devices, their mechanism is relatively simple, strong and effective. High rotational speeds of the rotors and high temperature of the exhaust gas render the turbochargers very sensitive to inappropriate operation. Assuming appropriate operation, a turbocharger can operate without failures for a long period (no less than 200 000 km of the vehicle mileage).

2. Types of turbocharger damage

2.1. Division

Types of turbocharger damage were divided in terms of damage causes. These are:

- inappropriate lubrication,
- presence of foreign objects,
- exceeding the admissible turbocharger rotational speed or excess pressure and exhaust gas temperature,
- corrosion.

The further part of this paper addresses each of the above-mentioned cases and describes causes and effects of the same.

2.2. Inappropriate lubrication

There are several reasons for inappropriate lubrication. First of them is related directly to **oil and its filter** – a turbocharger is lubricated with oil from the engine oil system. Because of operation in severe conditions and, for example, partial combustion of oil, the oil parameters may be deteriorated, which results in a change of the oil density, viscosity and resistance to foaming. The oil may be contaminated, which may cause micro-machining, scratching or grooving of the top layers of the assemblies. Contaminated oil causes accelerated wear of the bearings and destruction of the mid part where the bearings are fitted. The oil may have low original quality or be inappropriately selected for the engine. It is also significant to select an appropriate oil filter of adequate parameters. A damaged or congested filter may considerably deteriorate the turbocharger lubrication.

To sum up, a damage of turbochargers may in this case be a result of:

- poor engine oil quality,
- deterioration of the oil quality as a result of partial combustion of oil.
- failure to ensure periodical replacement of oil and its filter,
- congested, damaged or poor quality oil filter,
- failure of the oil filter bypass valve,
- engine wear,

The effects of the damage are in the first stage visible in the form of scratches on the race of the transverse (Fig. 2.1) and longitudinal bearings (Fig. 2.2).

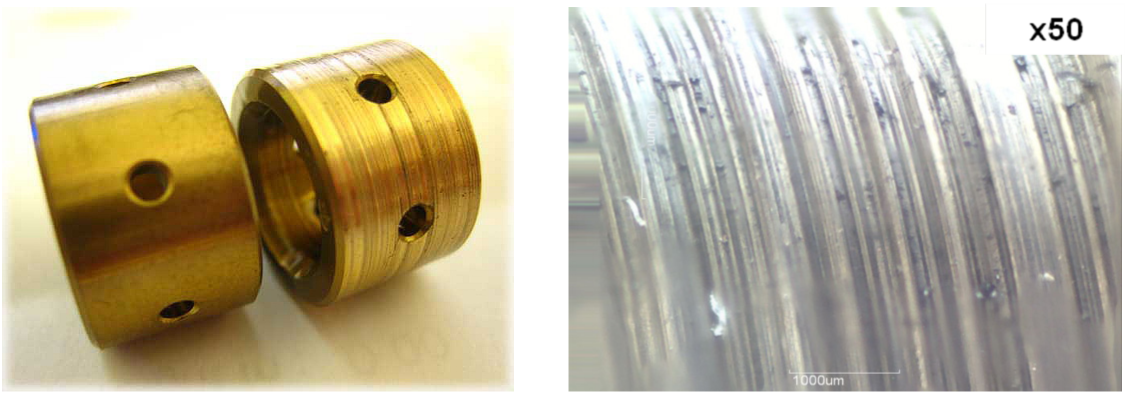

Fig. 2.1. Scratches of transverse bearings

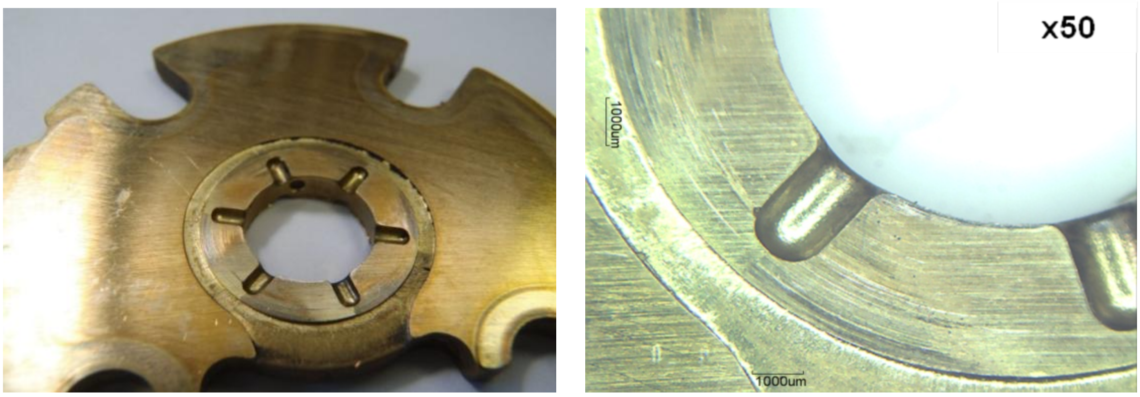

Fig. 2.2. Scratches of longitudinal bearings

Damage of bearings leads to a seizure of the turbocharger shaft journal (Fig. 2.3). The resulting gaps may cause scratching of the turbine or compressor rotor vanes against the body surface, which results in damage of the same (figs. 2.4).

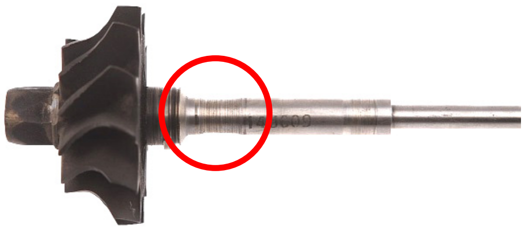

Fig. 2.3. Deep scratches on the shaft caused by contaminated oil

Fig. 2.4. Damage of the body surface on the side of the turbine

The compressor (Fig. 2.5) or turbine rotor vanes are also damaged.

Fig. 2.5. Damage to the compressor vanes caused by excessive shaft play

As can be observed, a single damage is followed by another. In order to prevent such type of damage, oil and filters should be of good quality and need to be replaced with each repair of the turbocharger. Additionally, oil and filters should be replaced at regular intervals in accordance with the vehicle manufacturer's recommendations or even more frequently when used in arduous dusting conditions.

Examples of irregularities in the lubricating process also include **oil starvation**. Precisely matched parts of the turbocharger have to operate in permanent oil film. In case of even small lubrication disorders, rotating and stationary parts may contact, which will lead to serious damage immediately. Aside from lubricating of the cooperating parts, oil also works as a cooling medium.

Reasons for momentary oil starvation:

- inappropriate turbocharger startup after reassembly or repair,
- renewal of oil and its filter,
- a long dwell time in vehicle operation,
- low pressure of oil due to poor functioning of the lubrication system,
- contamination of oil, for example, with coolant or fuel,
- inappropriate engine start in low temperatures,
- operation of the engine in overload conditions (high load for low engine speeds).

Because of oil starvation, especially a prolonged one, the surface of the shaft and the bearings will, get polished and will seize (Fig. 2.6).

Fig. 2.6. Seized and damaged surfaces of the bearings

Lubrication problems may also be caused **by lack of oil or considerable decrease in the oil pressure**. Oil pressure deficit is the most serious form of oil starvation incidents and may be attributed to:

- bent, broken or congested turbocharger oil duct,
- faulty oil pump,
- low pressure of oil in the engine oil pan,
- penetration of air into the lubrication system,
- lack of lubrication due to excessively long operation of the vehicle in high terrain inclination conditions.

Considerable shortage of oil pressure for an extended period (exceeding 8 - 10 seconds) causes damage to the turbocharger bearings. This results in polishing and burning of the bearings surface (Fig. 2.7) as well as discolorations of the shaft resulting from significantly increased temperature (Fig. 2.7).

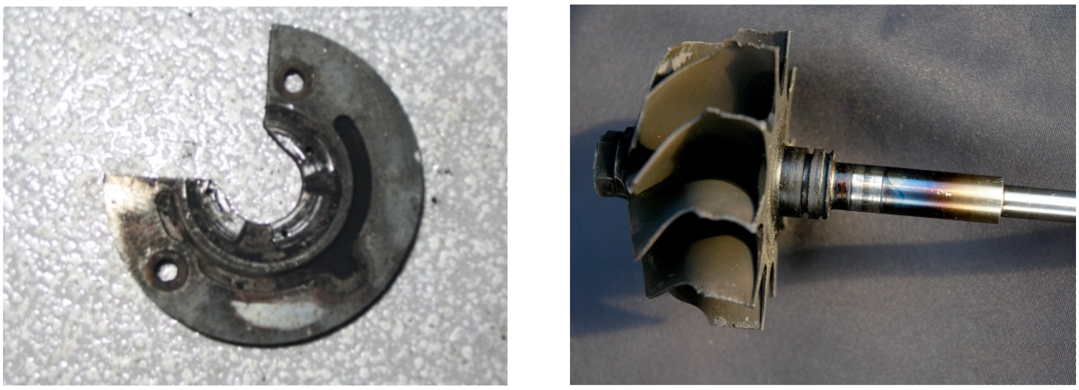

Fig. 2.7. Overheated longitudinal bearing and seized surface of the turbocharger shaft

The lack of oil is more dangerous than its instantaneous shortage and more frequently leads to seizures of the surface of the bearings and the shaft, including those of the longitudinal shaft, which consequently leads to a destruction of the turbocharger.

Another lubrication problem is **inhibited outflow of oil from the turbocharger**. Reasons:

- congested drain duct of the turbocharger (Fig. 2.11),
- blowby in the piston and cylinder system (especially for excessive pressure above 50 hPa),
- congested venting system,
- excessively high oil level.

Disorders in the oil outflow may cause a decrease in the oil pressure and deterioration of the lubrication, which may lead to effects similar to those connected with decreased lubrication pressure or oil starvation.

2.3. The presence of foreign objects

The damage is caused because of penetration of foreign objects (elements of the air filter box or the filter itself, fragments of piston rings or spark plugs) into the exhaust or intake system. Foreign objects may also include tiny fragments of pistons or valves and carbon deposits from the combustion chamber. Damage caused by foreign objects is visible on the turbine and compressor vanes. The use of a compressor with damaged vanes (the turbine and the compressor vanes) leads to further damage, as the system is unbalanced. Examples of damage caused because of penetration of a foreign object into the compressor and turbine are presented in Fig. 2.8 and 2.9 respectively.

Causes:
- foreign objects left after reassembly or repair,
- ineffective air treatment system,
- loss of airtightness or damage to the engine air intake system,
- damage to the engine (damaged valve guides or heaters).

Damage resulting from the penetration of foreign objects into the exhaust or intake system result from negligence of the staff and may cause widespread damage, which can render any turbocharger irreparable. The mechanism of damage is of erosive character and depends on the size of a foreign object getting onto the rotor vanes. Even the smallest element carried with the air or exhaust gas flow has a strong influence on the vanes as a result of considerable gas flow energy.

Fig. 2.8. Damage following penetration of a foreign object into the compressor

Fig. 2.9. Damage following penetration of a foreign object into the turbine

2.4. Exceeding the admissible rotational speed of the turbocharger shaft or excessive pressure and temperature of the exhaust gas

Excessive increase of the turbocharger shaft speed in connection with an increase in the exhaust gas temperature can be observed in cases of inappropriate changes in the injection map (unauthorized software update). Excessive speed of the rotor may also be caused by unlimited charging pressure for higher engine speeds. This may be caused by blocking (carbon deposits) of the geometry in a setting for low engine speeds. In addition, the absence of charging pressure control favors uncontrolled increase in the rotor speeds. Such situation occurs in the case of damage to an electrical adjuster, the electrical system of a vehicle or loss of airtightness of the turbocharger pneumatic control system. On the other hand, loss of airtightness of the intake system of a vehicle on the compression side cause the turbocharger to operate with smaller loads, which also leads to an increase in the turbocharger shaft speed. Increased pressure of the exhaust gas generates axial forces influencing the turbine rotor. This results in an increased wear of the thrust bearing and turbocharger seal rings, which may be caused by inappropriate engine operation.

On the other hand, overheating of the turbocharger is caused, above all, by deterioration of its cooling conditions, which is mainly caused by excessively quick engine stop after operation for a prolonged period, particularly under high loads. This type of overheating constitutes one of the most dangerous factors causing heavy damage of the compressor rendering it irreparable.

Overheating leads to the accumulation of carbon deposits (from burnt oil), which results from excessive temperature of the exhaust gas or excessively quick stop of the engine after operation. This may be prevented by letting the engine idle for a period of approx. 1 minute (the period of time necessary to cool the turbocharger). The transfer of high temperature from the turbine shroud to the mid part of the turbocharger causes oil burning and corrosion of the turbocharger bearings. The main damage is observed on the grooves and seal rings of the turbine shaft (Fig. 2.10) as well as on the bearing and the bearing pins.

Fig. 2.10. Damage of the groove, the seal ring and the longitudinal bearing pins

Damage observed in the areas of the turbocharger seals lead to oil losses. Additionally, it leads to unintended outflows of air and exhaust gas (Fig. 2.11).

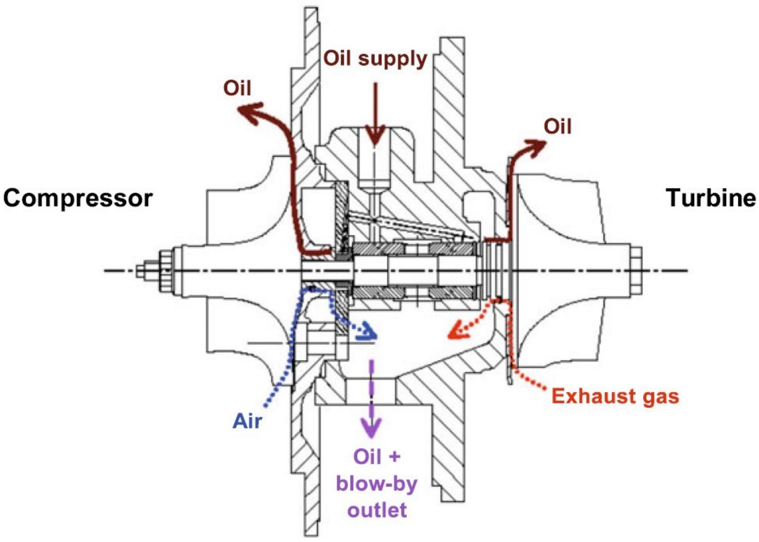

Fig. 2.11. Sources of oil leakage and blowby of air and exhaust gas in the turbocharger [2]

Burnt oil also causes congestion of the oil outflow in the midpart of the shroud (Fig. 2.12). This usually results in a destruction of the shaft and the midpart of the shroud in places where it cooperates with the seal ring and the bearings.

Fig. 2.12. The result of overheating – congested (by oil originating carbon deposits) turbocharger drain duct

Causes:
- congested or worn air filter element,
- excessively quick engine stop after operation,
- inefficient engine power system as connected with inappropriate operation of injectors,
- excessively long period of operation without oil change,
- blowby of air and exhaust gas,
- inefficient injectors,
- inappropriate assembly of the turbine,
- inefficient turbocharger lubrication system,
- inefficient oil return system (defects in engine crankshaft venting),
- excessive temperature of the exhaust gas (Fig. 2.13).

Fig. 2.13. Chipped and melted turbine rotor vanes because of high exhaust gas temperature

2.5. Corrosion

Corrosion of a pressure adjuster is a relatively rare damage in the area of the turbocharger (Fig. 2.14). Such a failure results in the absence of reaction of the turbocharger to the signal from the acceleration pedal. Such situations are often the case in Volkswagen Group vehicles.

Fig. 2.14. Corroded pressure adjuster of the turbocharger in Skoda Octavia

3. Conclusions

The development of diesel engines always aims at decreasing the fuel consumption, increasing the power to capacity ratio, reducing the engine weight, ensuring reliability of operation under various operating conditions and increasing its durability. One of the long known methods of engine improvement is engine supercharging. Structural solutions applied in the supercharging equipment have greatly evolved. Despite the fact that a turbocharger is a high precision device, its mechanism is relatively simple, strong and effective. If properly operated, a turbocharger can operate reliably for years despite the fact that its operating conditions are very arduous. Turbochargers do not require any special maintenance. A periodical inspection of the turbocharger fitting in the engine is usually sufficient, which ensures appropriate operation of the turbocharger. The discussed operating problems of modern diesel engine supercharging systems widely investigated during the author's research and expert practice are to some extent the consolidation of the author's activity, which may contribute to further works on the improvement of diesel engine supercharging systems.

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