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OPERATING FLUIDS CONTAMINANTIONS AND THEIR EFFECT ON THE WEAR OF ELEMENTS OF A MOTOR VEHICLE'S COMBUSTION ENGINE

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Summary

The contamination parameters of basic operating fluids of combustions engines of mechanical vehicles: air, fuel and engine oil. It was shown that mineral (road) dust decides on the consumption of abrasive connection elements of an engine. The mechanism of abrasive wear of two cooperating surface of the piston-rings-cylinder abrasive connection element of the combustion engine was shown. It was shown that the dust grains of sizes d_z equal to minimum h_{min} thickness of the oil film cause the largest consumption. It was shown that in the air purified, behind an air filter, there are always dust grains of sizes below 2÷5 μm. The effect of accelerated wear of a cylinder liner of the engine operated with a defective air filtration system was shown. It was shown that dust grains of sizes below 5 μm in the operating fluids are also the cause of the accelerated engine components wear. It was proven that (after replacing the filter cartridge), the operation period of a partition air filter (paper, non-woven fabric) is characterised by low efficiency and filtration precision. It was shown that contaminants in the fuel not only cause abrasive wear on the surfaces of the injection system elements but also erosive wear of injector elements.

Keywords: operating fluids, contaminations, abrasion and erosion wear, air, fuel and oil filters, filtration efficiency and accuracy

1. Introduction

Modern combustion engines of mechanical vehicles require many operating fluids for proper operation. Every operating fluid fulfils a different function, hence their different properties and chemical composition. The basic operational fluids of a modern car are: atmospheric air taken from the atmosphere, fuel, engine and transmission oil. In the car,

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there are operating fluids such as coolant, brake fluid, refrigerant in an air conditioning system, electrolyte in a battery, fluid in shock absorbers in smaller quantities.

Purity of the operating fluids plays a very big role in obtaining high durability and reliability of engines and the entire vehicle. Properties of operating fluids deteriorate during vehicles operation as a result of contamination with all kinds of solids and liquids, e.g. water in fuel or diesel fuel, dust in the air, fuel, hydraulic oil, etc. Contaminations of operating fluids cause their physical or chemical aging. They also reduce the life of machines and vehicle components as a result of the intensification of corrosion, tribological and fatigue processes. The purity of the operating fluids, in particular the air sucked in by the engines, plays an important role in obtaining high durability and reliability of the combustion engines, guaranteeing obtaining the required overhaul periods.

2. Characteristics of operating fluids contamination

The basic operating fluid and simultaneously a basic component of the working medium of each engine is the atmospheric air. The air consumption of the engine is proportionally dependent on the engine power. In piston engines, approximately 700 kW is received from 1 kg/s (2800 m^3/h) of air consumed for combustion of the fuel. For example, the maximum demand of air is: for naturally aspirated engine with spontaneous ignition of the Peugeot 306 Sedan 1.9 D car – about 220 m^3/h, for an engine with spontaneous ignition with a turbocharger and intercooler of the Volkswagen T4 1.9 TDI card – 385 m^3/h, the engine of Scania R420 – over 1,600 m^3/h, and of the T-72 tank, it exceeds 3,400 m^3/h. Along with the air, combustion engines suck in large amounts of contaminations, especially when the vehicles are operated along unpaved roads and off-road. Into other operating fluids, the contaminants may enter from the atmosphere as a result of distribution and storage operations, through leaks in systems, during maintenance works or may formulate in them as a result of physical or chemical processes. Due to the tribological processes occurring in the engine's friction connections, mineral contaminations contained in the air, which accelerate wear of the cooperating surfaces are the most important.

A common, harmful to operated vehicles, air pollution is polydisperse road dust, which is lifted from the surface of the ground during the movement of mechanical vehicles or by the wind, forming a suspension in the air, where it then is sucked in by air capture inlets of the air filters. Dust grains of sizes d_z = 2 ÷ 10 μm persist long in the air, and thus are sucked in by the engines. Dust grains of d_z = 10 ÷ 50 μm represent a significant portion in the total air mass sucked in by the engines, when the engine operates under conditions of a high dust concentration in the air. Dust grains larger than 50 μm are in the air, on construction sites, mines, quarries, training grounds, but they quickly fall. They can be sucked into the engine, whose air capture inlet is at an altitude of (1 ÷ 2) m from the ground while driving in a column or in high winds and draught [2].

The main component of road dust is silica (SiO_2) and corund (Al_2O_3), whose share in the dust reaches up to (60 ÷ 95)% (Fig. 1a). According to the hardness evaluated based on the Mohs's 10-degree scale, in which talc corresponds to the hardness of 1 and diamond – to 10, silica (SiO_2) has the hardness of 7, and corund (Al_2O_3) – to 9. These minerals have hardness higher than the construction materials used in engines construction. The dust grains have usually very irregular shape (Fig. 1b), similar to polyhedral with sharp edges.

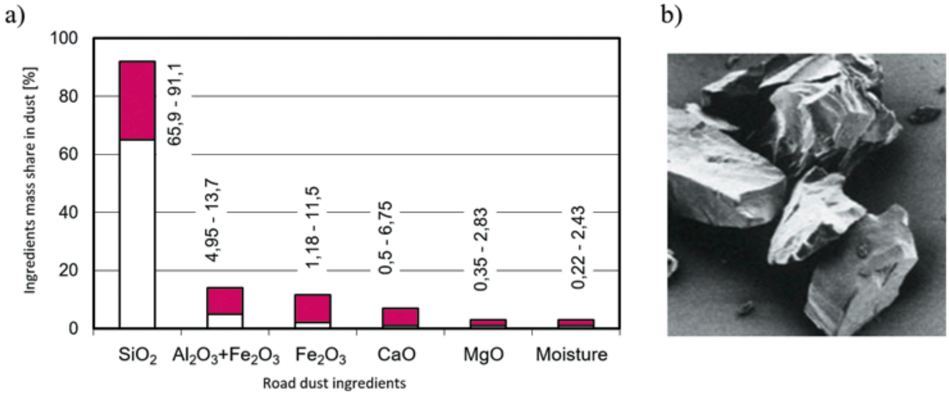

Fig. 1. Average chemical composition of road dust in Poland (a) [2], image of silica grains (b) [12]

The concentration of dust in the air, which is a measure of the dust mass (in grams or mg) contained in 1 m^3 of the air, is the variable size and depends on many factors. These include mainly the area and type of ground, the type of a wheel-axle assembly (wheeled, tracked) height above the ground, the type of traffic (a single vehicle or column), as well as weather conditions. The smallest concentration of dust in the air, about 0.001 g/m^3, occurs during the movement of vehicles along hard roads and streets; below 0.001 g/m^3 – in residential areas. The highest concentration of dust in the air, reaching (3.8 ÷ 7) g/m^3 [5], occurs when tracked vehicles move in the column along the polygon exercise squares with a dry ground (Fig. 2a). During the field works, the concentrations of dust in the air can reach 2 g/m^3 (Fig. 2b).

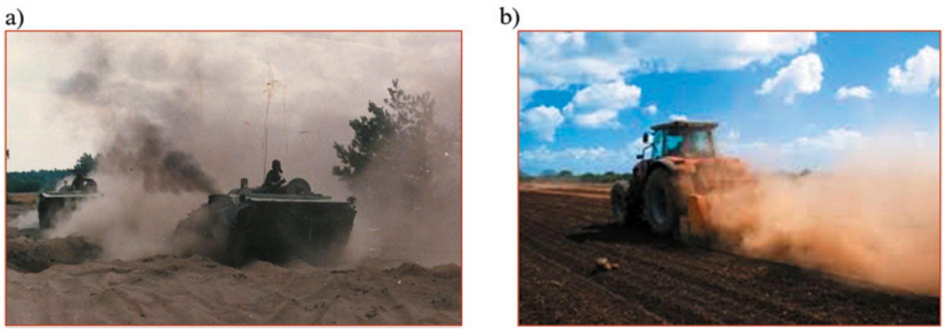

Fig. 2. Concentration of dust in the air:
a) when a column of infantry's combat vehicles drives along the sandy ground (own source),
b) during field works [17]

During a sandstorm, the dust concentration in the air reaches 10 g/m^3 [19]. Therefore, it is over 1,000 times greater than during the movement of vehicles on the streets.

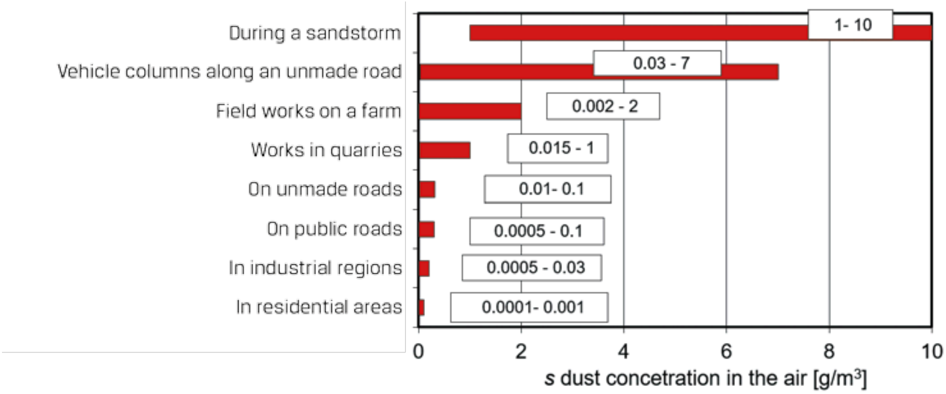

Fig. 3. Maximum dust concentration in the air depending on a region and a road type [19]

The results of tests of dust concentration in the air around an off-road passenger car operated in the summer along the polygon practice field presented in Fig. 4 show that the greatest dust concentration in the air s = 1.17 g/m^3 was registered under the bonnet, on the right side of the engine (measuring point no. 3 – Fig. 4b) for the case, when the vehicle moved behind a column of T-72 tanks [7].

Large dust concentrations in the air s occurring behind the column of tracked vehicles, much higher than behind the column of wheeled vehicles, result mainly from the type of the vehicles' wheel-axle assembly. The wheels of the car smoothly roll on the ground, while the track is pushed into the ground, which causes the ground lifting and scattering it behind the vehicle. The lowest dust concentrations in the air (regardless of the operating conditions) were recorded over the bonnet at the windshield (in the vehicle axis), which suggests the location of the air capture inlet into the engine. The impact of drive speed here is significant as speed increases from v = 10 km/h to v = 30 km/h, concentrations increase two times.

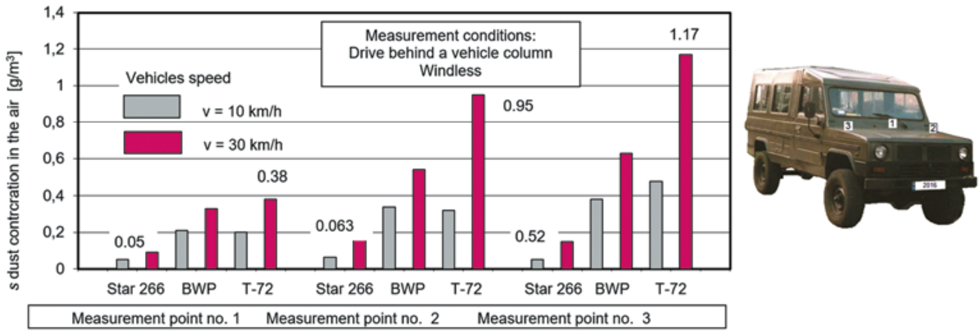

Fig. 4. Dust concentration in the air at the measuring points nos. 1, 2, 3 of an off-road passenger vehicle driving behind the column of: tanks T-72, BWP, Star 266 cars at different speeds [7]

External contaminations, mainly as mineral dust particles, enter into the engine oil through an engine power supply system together with fuel and air as well as during maintenance works. In the engine oil, there are internal and external contaminants, which are dust and metal particles that were not removed during the production, the products of the engine components wear, products of incomplete combustion, and products of chemical transformations. The concentration of contaminants in the oil is a function of time of the oil operation in and depends on: the oil type and properties, the quantity of added oil, oil filtration system type, and operating conditions.

In modern engines, the contaminant concentration in the oil is 0.1% by weight (after low mileage) to (0.5 ÷ 1.0)% of mass after the mileage of approximately 15 thousand km [2]. There are (75 ÷ 96)% contaminant particles smaller than 3 μm, and sizes smaller than (3 ÷ 10) μm are 99% of the particles number. The maximum contaminant particles size in the oil is 20 μm [2]. Contaminations of the motor oils contain (65 ÷ 87)% of organic substances and (13 ÷ 35)% of inorganic compounds. The inorganic substances are mainly contaminations entering into the oil from outside (silica) and the products of the engine components' wear. Internal contaminations are formed in fuels as a results of the influence of oxygen, elevated heat and catalytic effects of metals. External contaminations enter into the fuel as a result of warehouse-distribution activities and are represented by: dust from the environment, tank corrosion products, micro-organisms and products of their metabolism.

According to PN-EN 590, solids, which are retained during filtration under vacuum (from 2 to 5 kPa) of a 800 ml sample through a membrane filter with a nominal pore diameter of 0.8 μm, are considered to be responsible for fuel contaminations. The maximum level of solid contaminations marked in accordance with the above standard is 24 mg/kg. The Worldwide Fuel Charter, in the edition of 2013, for diesel oils of categories 2, 3, 4 and 5, lowers this level to 10 mg/kg. The contaminations sizes over 4 μm, 6 μm, and 14 μm included in the diesel oils of categories 2, 3, 4 and 5 should not exceed in numbers respectively: 18/16/13 [31]. Figure 5. shows an example image of a filter after filtration of the tested biofuel satisfying and not satisfying the requirements of PN-EN 590 [28].

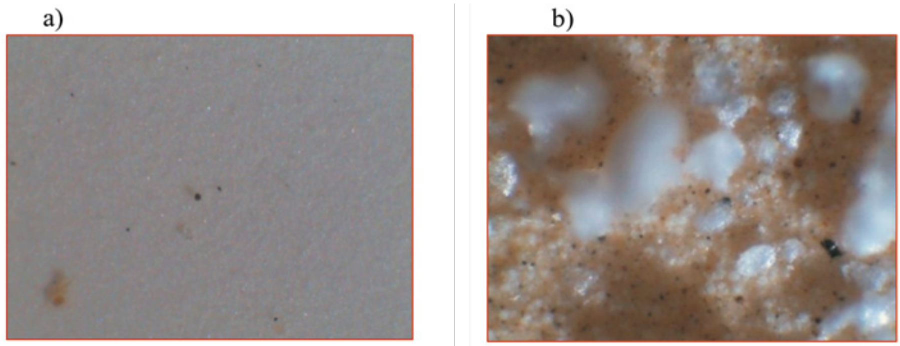

Fig. 5. Example image of a filter after filtration of the tested biofuel (100x zoom): a) satisfying the requirements of PN-EN 590 (rate 16/14/11), b) not satisfying the requirements of PN-EN 590 (rate 22/19/15) [28]

More and more often, engines with spontaneous ignition are equipped with direct fuel injection systems. These systems have very precisely made pumps and injectors, in which the fuel is fed directly to the combustion chambers under high pressure of up to 200 MPa. The precisely made injection equipment components are very sensitive to the quality of the used fuel – especially, to the solid contaminants level in the fuel. Figure 6 shows that the minimum required filtration efficiency of contaminations contained in the fuel for modern fuel systems is fixed at 85%. For older designs, e.g. with a line fuel pump, the required efficiency slightly exceeds 20%.

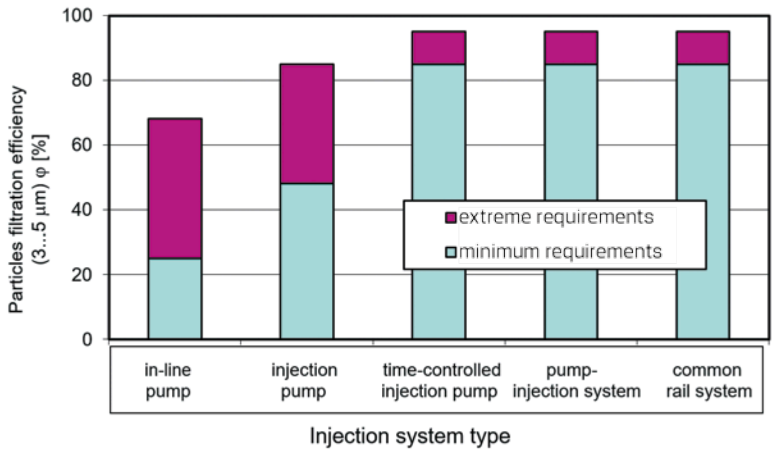

Fig. 6. Recommendations for minimum filtration efficiency of diesel oil filters [5]

In petrols, there are contaminant particles with sizes below 40 μm, and the particles with sizes below 20 μm dominate [2]. Contaminations of diesel oils contain from 30% to 60%, and even up to 90% of the inorganic substances [2]. The greater content of these substances (up to 60 mg/dm^3) is in the diesel oils in the tanks of vehicles used under field conditions.

3. Conditions of engine component surfaces' accelerated wear

During the operation of combustion engines with air, the significant amounts of contaminants enter into cylinders, but these are mostly dust grains with sizes below (2 ÷ 5) μm as modern air filters, where filter paper or non-woven fabric is a filter medium, operate with such precision. Larger dust grains enter into the engine cylinders as a result of the failure of the air supply system. At this time, dust grains with sizes much larger than 5 μm may enter into the cylinders together with the air. The contaminants enter into the engine cylinders also with fuel and oil but their amount is much smaller.

The abrasive wear occurs when a hard foreign objects get between two cooperating surfaces, sticking into the different depths, leading to deformation and cutting micro volumes of surface layers of the cooperating components. The literature is dominated by the view that the greatest wear is caused by the dust grains of sizes of d_z equal to the minimum h_{min} thickness of an oil layer needed to create a lubricant film between the cooperating surfaces, that is when there is the following relationship. For any other value of the quotient of h_{min}/d_z, connection wear decreases (Fig. 7) [11].

$$\frac{h_{\min}}{d_z} = 1 . \tag{1}$$

The minimum thickness of the oil film h_{min} between two abrasively cooperating surfaces is directly proportional to the temperature-dependent oil viscosity η, the C coefficient depending on the bearing dimensions, relative speed of lubricated surfaces υ, and inversely proportional to the P loading force and is expressed with the general dependency:

$$h_{\min} = \eta \cdot \frac{C \cdot \upsilon}{P} . \tag{2}$$

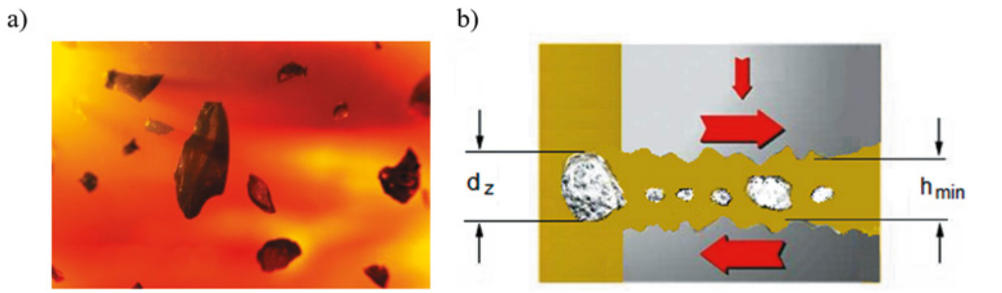

Fig. 7. Effect of solid particulates on a tribological connection:
a) contaminations suspended in the oil [1], b) condition of the maximum connection consumption [11]

For the set conditions of the engine operation, the oil film thickness h_{min} changes cyclically in a tribological connections area depending on the connection operating conditions. Between a cylinder liner and a piston rings, the oil film thickness is determined by the piston speed (Fig. 8).

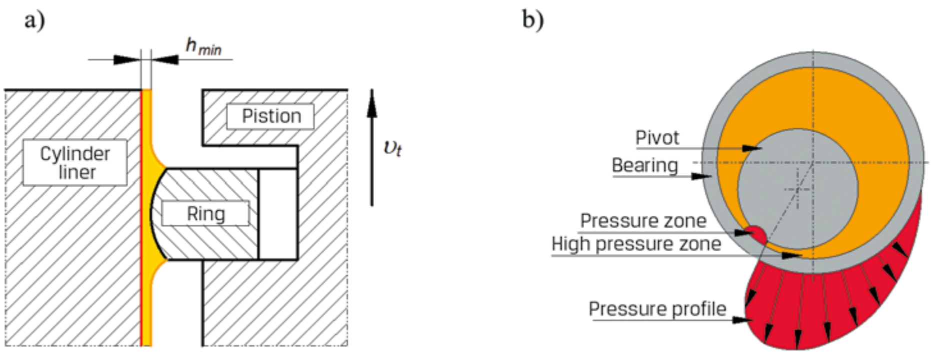

Fig. 8. Formation of an oil film in connections: a) P-R-C, b) pivot – bearing

Between the BDC and UDC dead centres, the piston (piston rings) speed is the largest, thus the thickness of the oil film in this area takes the maximum values. Changing the direction of the piston movement in extreme positions of the cylinder liner makes that its speed in this area is the smallest, and in BDC and UDC is zero, which leads to a reduction of the oil film or its complete disappearance. Therefore, there may be periods of even direct metallic contact between the piston ring and the liner.

Under these conditions, in theory, each particle with any small sizes can cause the wear. As a result of the oil film thickness changes, dust grains, which were between the cooperating surfaces, are crushed and grinded and can penetrate between two frictionally cooperating surface, where the oil film thickness takes small values.

In typical connections of a combustion engine, the oil film thickness specified in the paper [4] takes different values (Fig. 9).

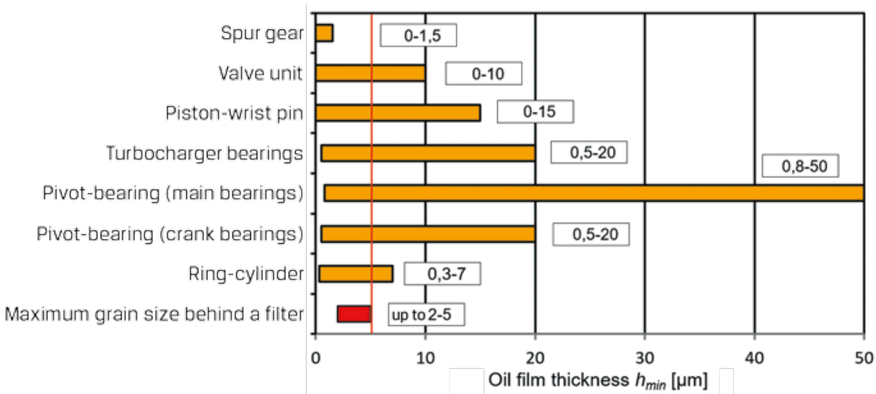

Fig. 9. Oil film thicknesses in typical combustion engine connections [4]

It is clear that even the smallest dust grains and those below (2 ÷ 5) μm will result in accelerated wear. It is believed that all the dust grains above 1 μm are the cause of accelerated wear, but the dust's abrasive aggressivity decreases when the dust grains sizes are below 5 μm. However, the dust grains below 1 μm are dangerous because they affect the cylinder sliding surface like polishing paste. Oil particles do not adhere to a polished cylinder bearing surface, which leads to breaking the oil film and accelerated wear.

The volume consumption of engine components due to the impact of dust depends on: the parameters of the sucked in dust, clearances between cooperating parts, design and operating engine parameters, material mechanical properties. The dust entering with the air into the engine cylinders affects the first piston ring, the piston, and the top cylinder part the most intensively. Applying by-pass filters in engine lubrication systems resulted exactly from the need to remove contaminants of with the dimension of below 1 μm from the engine oil.

4. Effect of inlet air pollutions on the wear of the "piston-piston rings-cylinder" connection

The accelerated wear of the cylinder liner may be a result of engine operation with an inoperative air filtration system. Figure 10 shows the image of such wear of a truck's cylinder liner.

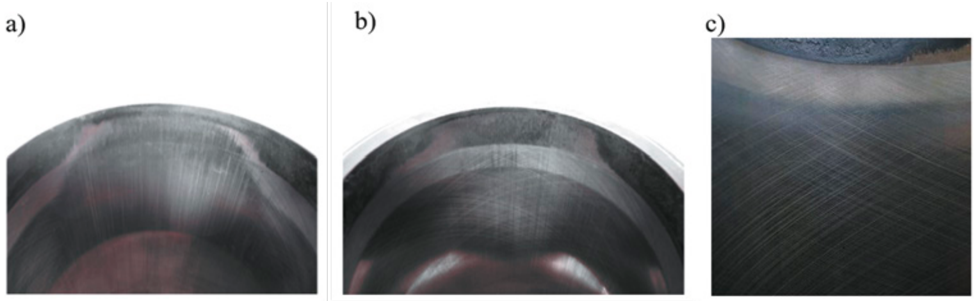

Fig. 10. View of a truck's engine cylinder bearing surface operated with an operative and inoperative air filtration system:
a) clear scratches band without honing traces,
b) visible single scratches band over surface treatment traces,
c) an operative air filtration system [9]

Abrasive wear of the cylinder bearing surface is visible in the form of parallel, continuous scratches bands along a forming cylinder liner in a cylinder bearing surface top area along approximately 1/5 of the circumference. Scratches were caused by hard and big dust grains. Scratch bands are so intense and deep that traces of final cylinder bearing surface treatment – honing – are invisible (Fig. 10a). Figure 10b shows much less wear of the cylinder bearing surface, seen as single scratches over the traces after surface treatment. Figure 10c shows the view of a truck engine's cylinder bearing surface operated with an operative air filtration system. Honing traces and combustion products deposits on the cylinder liner above upper dead centre of the first piston ring are clearly visible.

Figure 11 shows the formation of hollows in the cylinder bearing surface as a result of high-hardness particles' activity.

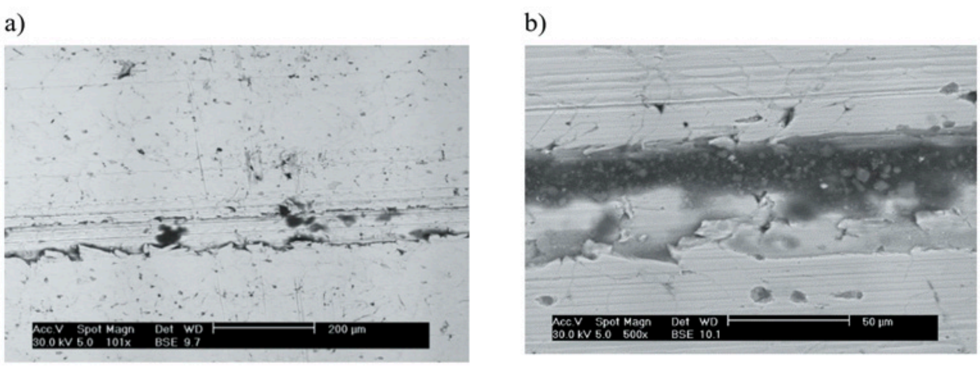

Fig. 11. Cracks in the cylinder bearing surface caused by dust particles [9]

In the cylinder bearing surface, there are numerous, irregularly places cracks parallel to the forming cylinder liner, with a width of up to 70 μm. The material losses in the form of cracks (furrows) are the result of the influence of high-hardness particles taking part in friction on the cylinder bearing surface. The scratches or rills size in a cylinder bearing surface is a representation of the size of foreign particles moving during friction between the cooperating components.

Figure 12 shows the topography of a top part of the truck engine's cylinder bearing surface operated with an inoperative air filtration system. On the cylinder bearing surface, in the ring TDC area, you can see foreign particles, while the scratch cluster with foreign particle deposits and cylinder bearing surface central zone's honing traces (50x zoom) can be seen in Figure 12b.

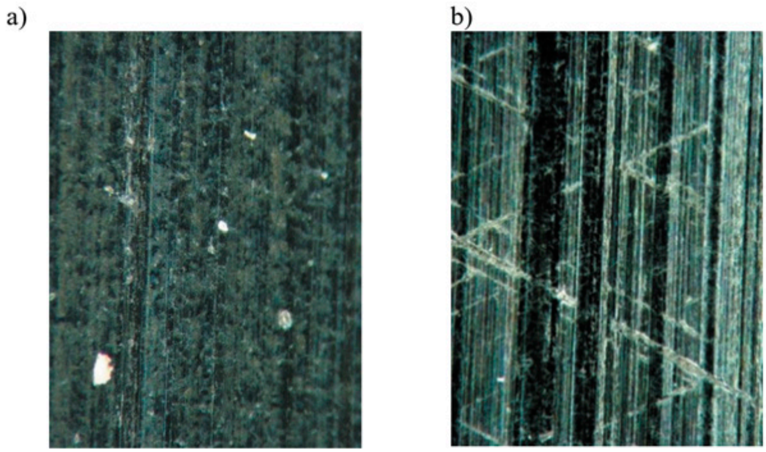

Fig. 12. Topography of the truck engine's cylinder bearing surface operated with an inoperative air filtration system:
a) foreign particles on the cylinder bearing surface in the UDC area (20x zoom),
b) scratches and honing traces of the cylinder bearing surface's central zone (50x zoom) [9]

Figure 13 shows the results of the P-R-C connection wear of a 4-cylinder engine with spontaneous ignition (V_{ss} = 1.3 dm^3, N_e = 66 kW at 4000 rpm, M_o = 200 Nm in the range of (1,750 ÷ 2,250) rpm), turbocharged, with charge air cooling and exhaust gases recirculation after 1,200 hours of operation according to a specified endurance test [21]. The greatest wear of the cylinder liners was registered in their upper part, in the plane perpendicular to (B-B) the engine axis, which is consistent with other studies results [11, 20]. The cylinder liner and piston rings wear caused by contaminants entering into the cylinder liner with the inlet air and contaminants in the oil causes the decline in the rod side area. As a result, there is a loss of the compressed agent, and thus the pressure drop at the end of a compression stroke, and consequently the tested engine power drop by approximately 2.5% and increase in specific fuel consumption by 3.4% (Fig. 13). The

P-R-C connection wear is also the increase in the intensity of exhaust fumes blow-through into a crank case (Fig. 14a), which increases the lubricating oil temperature, decreases its lubricating properties and blowing the oil through exhaust gases. The result of this is a loss of "a lubricant film," and as a result of which the system passes from fluid friction conditions to mitigated solid friction.

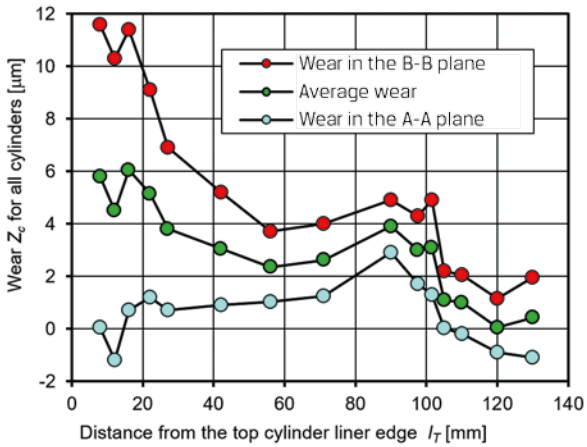

Fig. 13. Wear of a cylinder liner of a 4-cylinder, turbocharged engine with spontaneous ignition and power N_{emax} = 66 kW in a plane perpendicular (B-B) and parallel (A-A) to the engine axis [21]

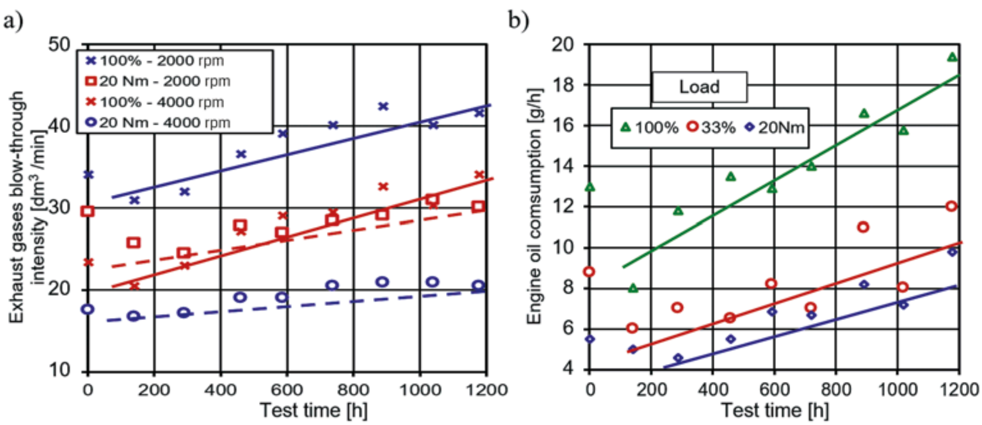

Fig. 14. Effect of the test on:
a) the engine exhaust gas blow-through at full and low engine load,
b) the engine oil consumption at various engine loads [21]

After 1,200 hours of operation at full load and 4,000 rpm, blow-through intensity increased by 61%. This accelerates considerably the engine oil degradation. The increased looseness in the P-R-C connection intensifies the phenomenon of piston rings operation, thus oil consumption and exhaust fused toxicity increase. At the same time, the engine oil consumption increased by 108%, 96% and 113% respectively at loads of 100%, 33% and 20 Nm (Fig. 14b).

The air filter is responsible for supply the air of appropriate quality (purity) in order to minimise the engine components wear to the engine cylinders. The dominant filter material, which is used for the filtration of vehicle operating fluids and, in particular, the intake air of modern mechanical vehicle engines, is filter paper, of which filter cartridges are shaped. In passenger cars, single-stage filters with a filter component in the form of a panel (Fig. 27) are used, while trucks and specialist cars equipped with two-stage filters, where the first filtration degree is an inertia filter (monocyclone or multicyclone), and the second one is a paper filter cartridge. Such designed filters provide target filtration efficiency up to 99.9% and the accuracy of over (2 ÷ 5) μm.

Fig. 15. Air filters and their filter cartridges:
a) single-stage filter of a modern passenger car [13],
b) NLG Piclon two-stage filter (monocyclone-porous barrier) of a truck [25],
c) PicoFlex two-stage filter (multicyclone-porous barrier) of a truck [22]

In mechanical vehicles driving under conditions of a very dusty air and when a filtration system has to satisfy requirements of a long service interval while keeping high filtration efficiency, three-stage filtration systems are used, which differ from the two-stage ones (multicyclone–filtration barrier) only in an additional filtration cartridge called "safety cartridge" and put serially behind the main filtration cartridge.

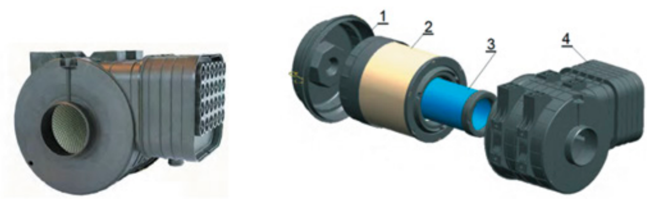

Fig. 16. SPB2 three-stage filter:
1 – cover 2 – filter cartridge, 3 – safety cartridge, 4 – multicyclone [29]

According to the paper [14] author, the newly mounted cartridge paper in the filter only after exceeding 25% (Fig. 30) of the projected mileage provides the required air filtration efficiency and accuracy. At that time, the contaminants mass entering into the engine cylinders with the air is significant, and the dust grains exceed the size of 5 μm several times. This period is characterised by high relative engine wear speed, several times higher than when working with a filter of nominal filtration efficiency. Therefore, frequent, unnecessary replacement of the filter cartridge may cause accelerated engine components wear.

Figures 19 and 20 show the results of the author's characteristics tests of a paper filtration barrier operating in a two-stage system: a single return cyclone with a tangential inlet and a cylindrical cartridge paper set behind it serially with respectively selected surface, so that the filtration speed does not exceed v_F = 0.06 m/s [5]. The characteristics of the effectiveness of filtration $\varphi_w = f(k_m)$, accuracy $(d)_{zmax} = f(k_m)$ and flow resistance and $\Delta p_w = f(k_m)$ of the cartridges made of two filter papers with different filter properties, with working names of VH1 and VH2 (table 1), where k_m is a liquid absorbency coefficient.

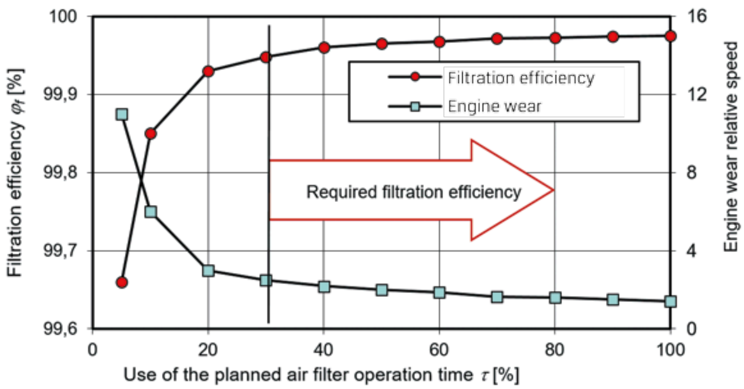

Fig. 17. Filtration efficiency and the engine wear speed in a function of time of air filter operation [14]

Absorbency coefficient k_m is defined as the dust mass retained on the surface of 1 m^2 of a filter paper in a time unit and referred with the quotient of the dust mass m_{PF} and a filter paper active surface A_c [5, 6, 8]:

$$k_m = \frac{m_{PF}}{A_c}\,[\mathrm{g/m^2}]. \tag{4}$$

For filter papers at reaching the permissible resistance Δp_{fdop} = (3 ÷ 5) kPa, the absorbency coefficient is k_m = (190 ÷ 220) g/m^2 [5].

Table 1. Parameters of the tested filter papers by the J.C. BINZER PAPIERFABRIK company

Item	Parameters	Units	Paper marking	
			796/1 VH 86 (VH1)	844 VH 86/4 (VH2)
1	Grammage	g/m^2	204	108
2	Thickness – load of 2 N/cm^2	mm	0.9	0.67
3	Flow resistance at 400 cm^3/s, A = 10 cm^2	mbar	6.7	1.04
4	Tear strength	kPa	385	212
5	Resin content	%	18.8	17
6	Maximum value of the pores diameter	μm	51	89
7	Average value of the pores diameter	μm	42	76

During the tests, dust concentration in the intake air of s = 1 g/m^3 was applied. The dust separated in a cyclone was sucked off ejectively continuously. The filtration efficiency was determined gravimetrically in subsequent measurement cycles, as the quotient of the test dust mass retained on the filter and supplied to it with the air. The PTC-D dust test, which is a domestic substitute for the AC-Fine dust, whose chemical and granulometric compositions are given in Figure 18, was applied.

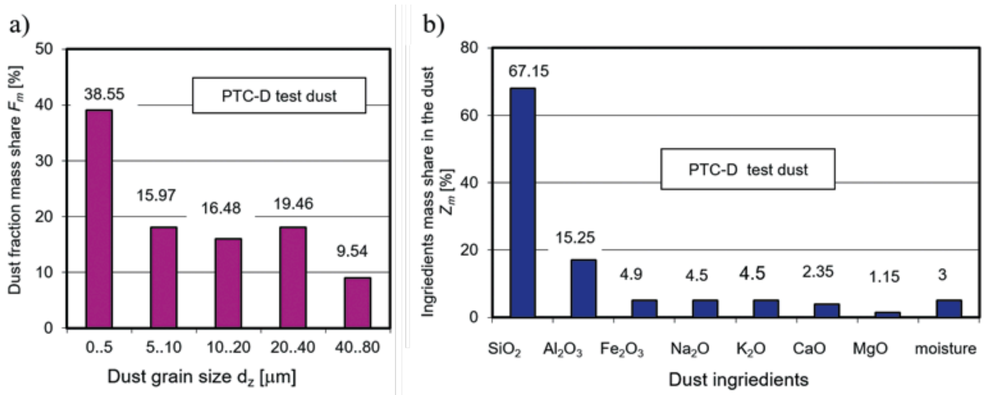

Fig. 18. Granulometric (a) and chemical composition (b) of the PTC-D test dust [27]

Because of the achieved filtration efficiency values, operation time of the tested papers can be conventionally divided into two periods (Figs. 19 and 20). The initial one (I_{VH1}, I_{VH2}), characterised by low filtration efficiency values, which increase steadily and rapidly with the dust mass quantity retained by the filter paper.

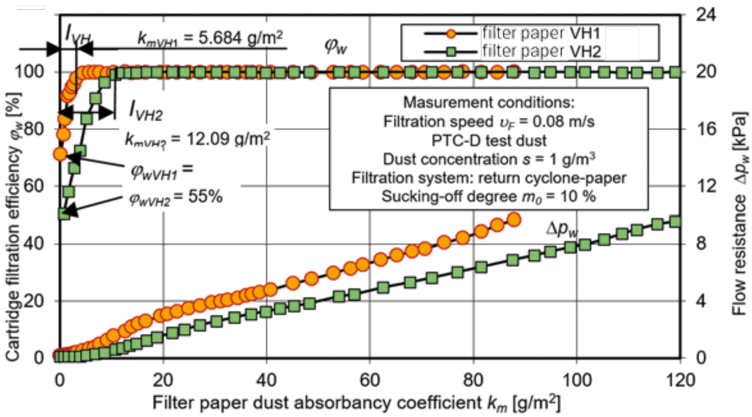

Fig. 19. Filtration performance $\varphi_{in} = f(k_m)$ and flow resistance $\Delta p_w = f(k_m)$ characteristics of the *VH1* and *VH2* filter paper in a function of the dust absorbancy coefficient k_m [7]

The initial period lasts from the beginning of the filtration process to the paper's reaching the maximum set filtration efficiency value. The fundamental filtration period after it is characterised by large (over 99%) and continuously but slowly increasing filtration efficiency values. In the case of the tested papers, separation zone of both periods at the time of the paper's reaching the filtering efficiency of φ_w = 99.5% was adopted [5]. After the first measurement cycle, the VH1 filter paper effectiveness reaches φ_{wVH1} = 77%, and the VH2 paper one's – only φ_{wVH2} = 55% – Fig. 19. Depending on the paper type, including the pore size (Table 1), this period can last up to 20% of the estimated vehicle's mileage limited by reaching the air filter's acceptable flow resistance. At this time, in the air purified by the filter cartridges, there was containing dust containing grain sizes with sizes below d_{zmax} = 13.4 μm for the VH1 paper and d_{zmax} = 13.8 μm for the VH2 paper (Fig. 20). It was assumed that the dust grain with the largest size d_{zmax} in the outlet air stream of the test filter cartridge is expressed by the paper filtration accuracy in the next measurement cycle.

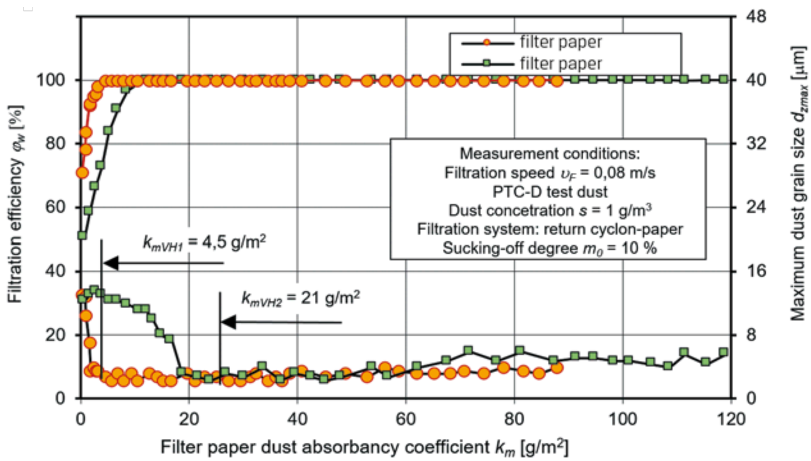

Fig. 20. Maximum dust grains size d_{zmax} in a function of the dust coefficient absorptivity k_m of the VH1 and VH2 filter paper operating behind the cyclone as the second filtration stage [7]

The dust grain smallest size (d_{zmax} = 2.7 µm) was recorded in the stream of the air purified by the VH1 filter paper at the absorbency coefficient k_m = 4.5 g/m². However, in the air behind the VH2 paper, the maximum dust grain size d_{zmax} = 2.7 µm was recorded much later, only after the paper's reaching the absorbency coefficient k_m = 21 g/m² – Fig. 20.

Figures 21 and 22 show the results of filter non-woven fabrics tests (Table 2), whose filter characteristics were defined under single-stage filtration conditions. The initial filtration time has small and systematically increasing filtration efficiency values with the retained dust mass quantity. This period lasts from the beginning of the filtration process to the tested non-woven fabrics' reaching the maximum set filtration efficiency value φ_w = 99.5%. The tested AC and B2 non-woven fabrics reached this value at absorbency coefficient of respectively: k_{mB2} = 34,5 g/m² k_{mAC} = 93 g/m². In the analysed filtration period, in the air purified by the non-woven fabrics, there was dust containing grains with sizes in the range of d_{zmax} = (6.2 ÷ 30) µm (Fig. 22). The dust grain smallest size d_{zmax} = 7.8 µm and d_{zmax} = 6.2 µm was recorded in the stream of the air purified by the B2 and AC non-woven fabrics at the absorbency coefficient k_m = 72.4 g/m².

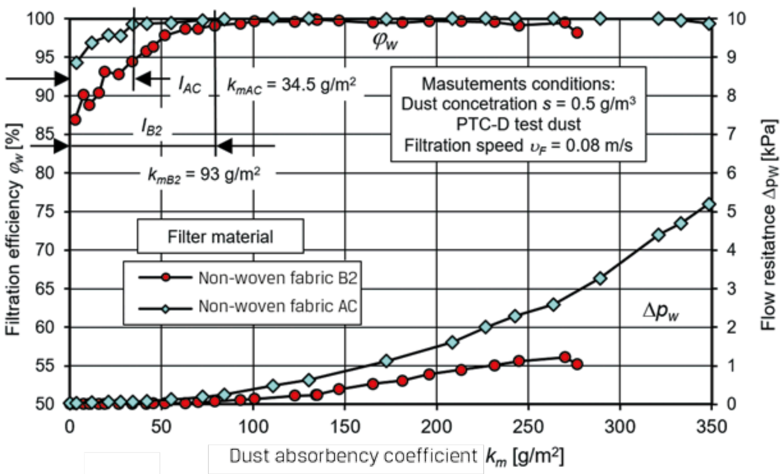

Fig. 21. Filtration efficiency $\varphi_w = f(k_m)$ and flow resistance $\Delta p_w = f(k_m)$ characteristics in a function of the dust k_{m1} absorbency coefficient of the B2 and AC filter non-woven fabrics specified under single-stage filtration conditions [6]

The filter paper (φ = (55 ÷ 77)%) and non-woven fabrics (φ = (86 ÷ 94)%) low efficiency is associated with the presence of large (d_{zmax} = 30 μm) of dust grains in the air purified in the initial, although short, operation period. This may have affect the accelerated wear mainly of the P-R-C connection, as shown in papers [9, 11, 14, 20, 21, 30].

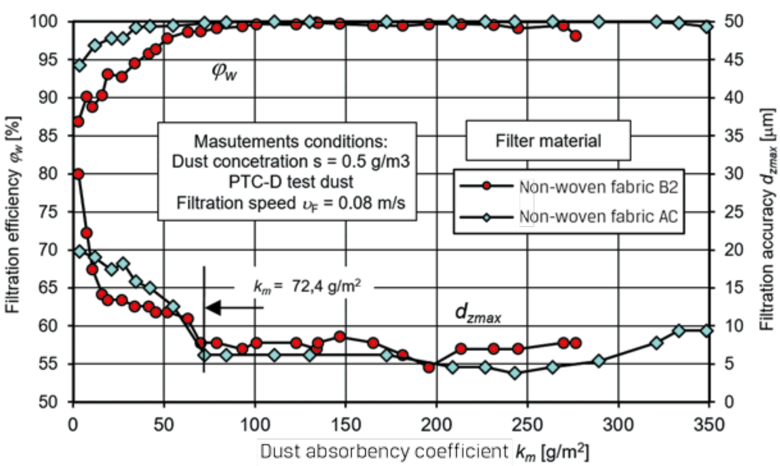

Fig. 22. Filtration efficiency $\varphi_w = f(k_m)$ and accuracy $dzmax = f(km)$ characteristics in a function of the dust km absorbency coefficient of the B2 and AC filter non-woven fabrics specified under single-stage filtration conditions [6]

Under real conditions, such an air filter operation status occurs after replacing the contaminated filter cartridge with a new one. As the filtration efficiency stabilises at (99.5 ÷ 99.9)%, in the purified air, there are dust grains with maximum dimensions below d_{zmax} = (5 ÷ 7) μm. The filter reaches the highest filtration efficiency (99.9%) in the final operation period that is when its flow resistance approaches the permissible resistance values Δp_{fdop}, which is the filter cartridge replacement criterion.

Because of the high efficiency value retained impurities and high accuracy of the filter cartridge should, therefore, be operated as long as possible. However, with the increasing mass of the dust retained on the filter cartridge increases not only the efficiency, but also the flow resistance of the air filter, which can cause a decrease in engine power. That is why the manufacturers of modern passenger cars recommend filter cartridge replacement after specified mileage (30 ÷ 60) thousand km, which corresponds to the filter's reaching the permissible resistance values of about Δp_{fdop} = 3 kPa. In the air filters of trucks and special cars, the permissible resistance sensors of the nominal values of the range Δp_{fdop} = (5 ÷ 8) kPa are applied. Therefore, the filter cartridge replacement earlier than it is recommended by the user manual or before the permissible resistance signalisation occurs is a serious mistake made by users of vehicles and in service stations.

5. Engine oil contaminations effect on engine abrasive connections wear

Part of air pollution that enters into the engine cylinders through the air supply system is burned; the other part is removed along with the exhaust gases. Only (10 ÷ 20)% of the contaminants entering into the engine through an intake system sediment on the cylinder liner walls. This part of the contaminants, being predominantly of mineral origin, of dust grain sizes below (2 ÷ 5) μm, forms with the oil some kind of abrasive paste, which destroys the piston-piston rings-cylinder (P-R-C) connection surfaces structure in contact with them. As a result of the piston movement towards the BDC, the rings scrap the oil from the cylinder bearing surface together with the contaminants into a sump. After entering into the lubrication system, the contaminants are distributed through the oil system to these engine tribological areas that are lubricated with oil – for example, into the connections of: pivot-crankshaft bearing, pivot-camshaft bearing, valve guide-valve stem, causing their accelerated abrasive wear.

The contaminants with a dimension below 1 μm are especially dangerous for the cylinder bearing surface. As a result of their operation, there occurs the so-called cylinder bearing surface polishing, as a result of which oil particles do not adhere to it, resulting in the oil film breakage, mitigated solid friction, and, therefore, increased consumption.

As a result of increased engine components wear, there occur the decrease in power and the increase in specific fuel consumption. In the Cummins N 14 engine, in which the oil was replaced cyclically, every 25 thousand miles, over 18% loss of power in relation to the new engine and the engine, where the oil was replaced twice often, was recorded (Fig. 23) [11]. As the oil was replaced, the contaminants that were the cause of the P-R-C connection components accelerated wear were removed. The less frequent oil replacement resulted in the contaminants accumulation, which resulted in increased wear of this connection and a decrease in power.

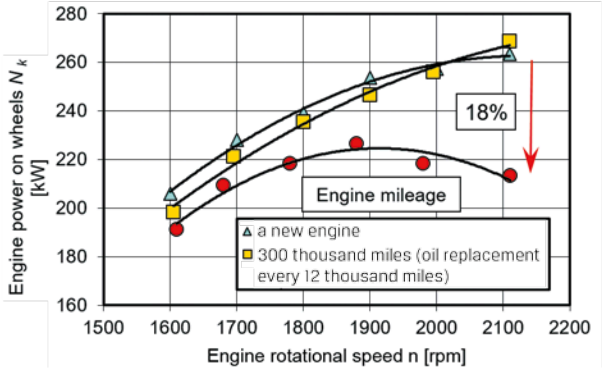

Fig. 23. The Cummins N14 engine power change – the new one and after different vehicle mileages with oil replacement every 12 and 25 thousand miles [11]

The Contaminants in the oil result in scratches and damages to the connections surfaces (Fig. 24). They can sediment on the bearing shells material, and their presence effects in the form of abrasive wear will be felt even after the oil replacement.

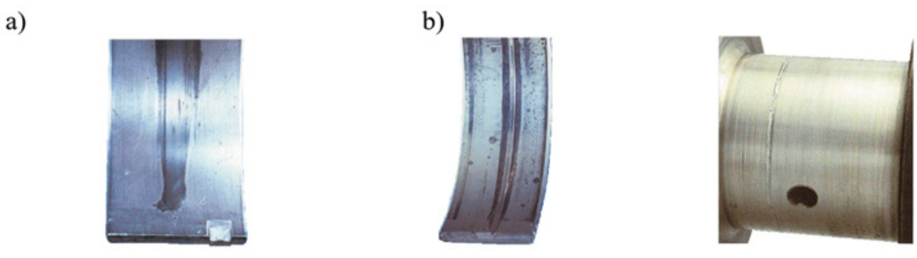

Fig. 24. View of engine shells (a) and crankshaft pivot (b) of the car operated with an inoperative air filtration system [26]

Main flow filters ensure the engine oil purity. These are usually filters replaced in its entirety with a filter cartridge sealed in a tin or plastic housing screwed to an engine block (Fig. 25a). The current tendency in the construction of engine oil filtration moves toward two filter types: a main flow filter retaining larger contaminants, and a by-pass one of high-precision filtration, through which (5 ÷ 10)% of the oil stream flow from the engine cycle. The standard engine oil filter medium retains particles with sizes of below 9 μm, and the composite one – below 4 μm, and thanks to a multi-layer structure, it separates particles with a diameter of 10 μm 20 times better.

Applying the by-pass filters resulted from the need to remove from the finest contaminants with a diameter of below 1 μm causing the so-call the cylinder bearing surface polishing from the engine oil. Two by-pass filter types are applied: with a filter cartridge or as centrifugal ones (Fig. 25c). The main flow and by-pass filters can be in one unit (Fig. 25b) or in a so-called filter module (Fig. 25 d), which also features an oil cooler, a fuel filter and sensors. Thanks to application of one housing, the cables connecting the particular filter types can be eliminated and the oil can be rapidly heated or cooled (depending on a current need), which is suitable for the drive unit optimal operation.

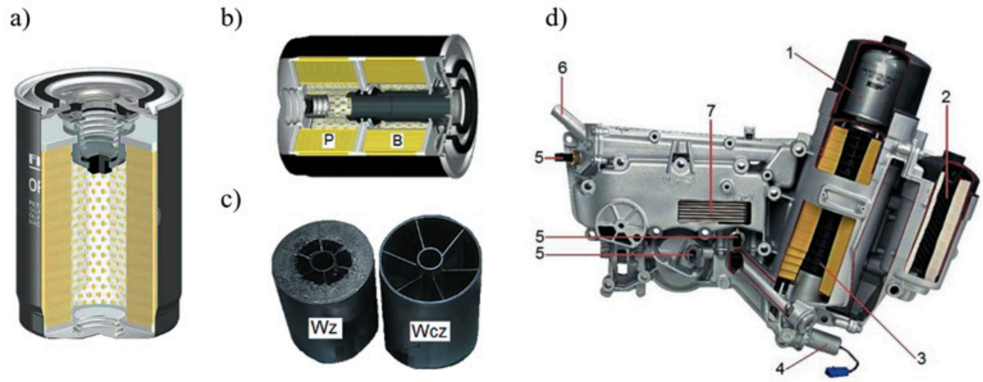

Fig. 25. Engine oil filtration systems:
a) traditional spin-on filter, b) filter unit: main flow (P) and by-pass filter (B) [24], c) contaminated (Wz) and pure (Wcz) by-pass (centrifugal) filter rotor, d) filter module used in Mercedes-Benz, MAN and Deutz: 1 – by-pass filter, 2 – fuel filter, 3 – main flow oil filter, 4 – solenoid valve, 5 – pressure and temperature sensors, 6 – coolant drain to the driver's compartment heating system, 7 – oil cooler [33]

6. Fuel contamination effect on the injection system components accelerated wear

Figure 26. shows the manners of the contaminants' entering between plunger and barrel assemblies sealing surfaces of a classic injection pump's pumping section. Large grains that get between the cooperating surfaces, are stuck, deformed or fragmented into smaller particles, causing that quite characteristic, local scratches and dimples and even serious material losses of these parts form on the cooperating surfaces.

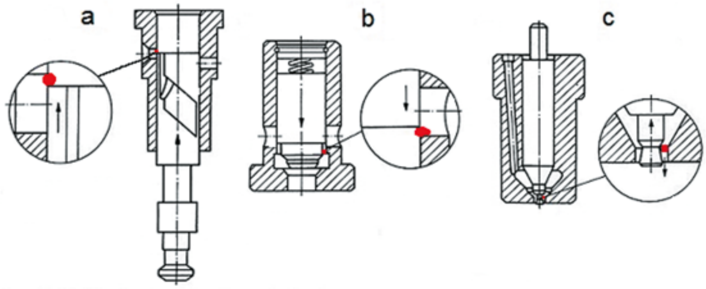

Fig. 26. The manners of the contaminants' entering between plunger and barrel assemblies sealing surfaces: a) in a pumping section, b) in a pressure valve, c) at a washer pivot

On the basis of microscopic observations, the Authors of the paper [18] state that the plunger and barrel assemblies wear processes occur mainly in the part over a groove controlling a fuel dose (Figs. 27b, c and d). The dominant wear mechanisms in this area are the plastic deformations and chasing as well as micro cutting of the surface caused by hard contaminants in the fuel, with grain sizes (of (1 ÷ 2) μm) comparable with the oil film thickness. Figure 27a shows a new, undamaged piston surface fragment, where the component grinding traces are clearly dominant.

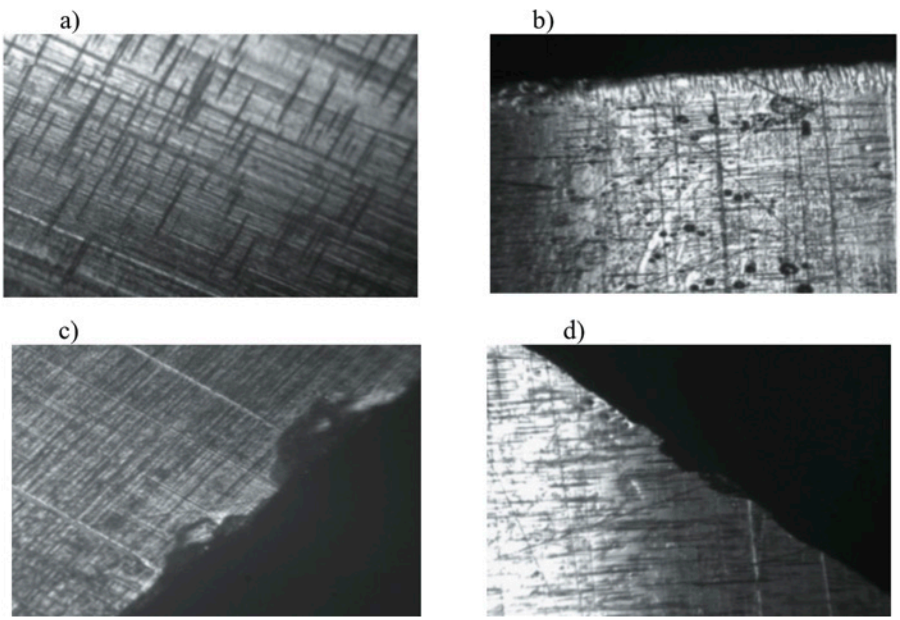

Fig. 27. Image of an injection section piston surface: a) a new piston surface fragment (the grinding traces clearly dominate), b, c, d) the piston surface area after operation (125x zoom) [16]

The classic injection pump's "piston-cylinder" connections wear increases loosenesses' clearance, thus increasing the hydraulic losses during pressing, which results in a reduced fuel dose and change in the injection pump's pumping characteristics (Fig. 28).

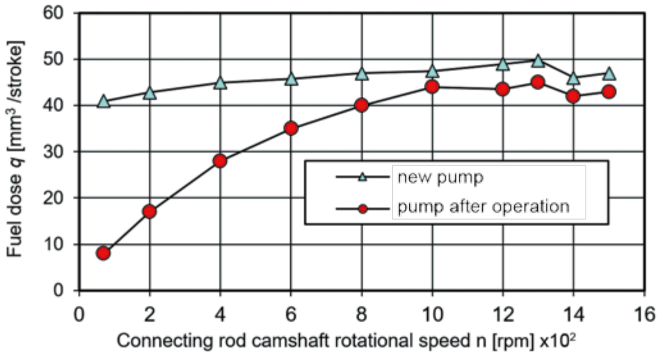

Fig. 28. Classic injection pump characteristics – the new one and after operation [7]

The contaminants in the fuel, which exude at high speed, cause erosive wear. Figure 29 shows the dust $d_z > 5$ μm grains concentration in the fuel effect on the erosive wear [30]. The application of a fuel filter fuel definitely reduces this wear. A filter with filtration efficiency of φ_2 = 55% reduces the injector wear intensity by over 50%, and the filtration efficiency of φ_2 = 88% reduces the consumption ten times.

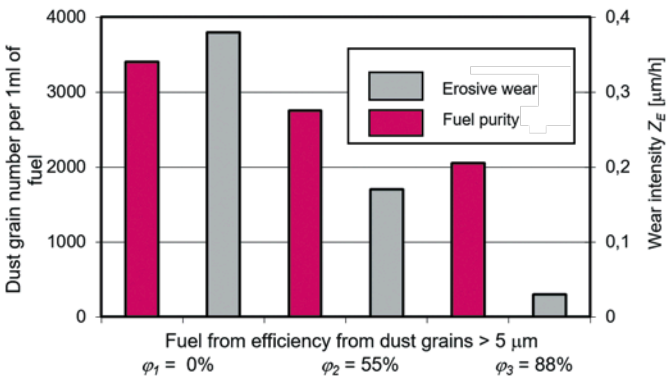

Fig. 29. Contaminants in the fuel effect on the injector erosive wear intensity [30]

Figure 30 shows examples of injecting system components' erosive wear at insufficient fuel filtration. The wear of an injecting system solenoid valve seat of a PD engine with spontaneous ignition of a utility vehicle. Longitudinal dimples caused by particles in the fuel erosions (Fig. 30a) are very visible. They cause internal leakages and thus reduce the injected fuel dose. In practice, this type of damage manifests with decreasing engine power, uneven operation and increased soot emission. Similar images of wear in the form of material grooves and formed scratches were observed for a CRI injector valve (Figs. 30b, c).

Fig. 30. Wear of injection system components at insufficient fuel filtration:
a) erosive one of a solenoid valve socket [5], b, c) of a CRI injector valve seat [10]

Figure 31 shows abrasive wear of injection elements visible as the control piston and firing pin peripheral abrasions caused by low fuel quality.

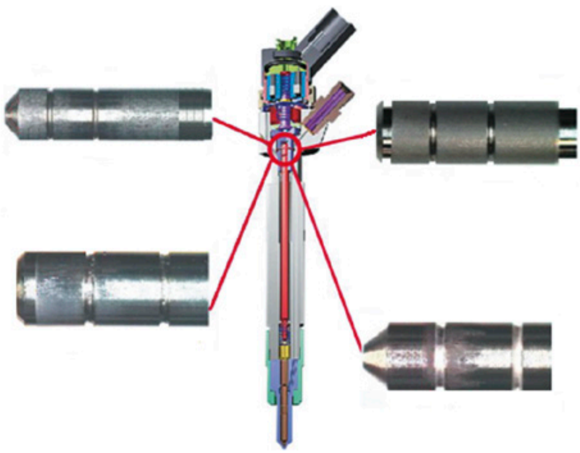

Fig. 31. Example abrasive wear of injection components visible as control piston peripheral abrasions [23]

The view of a mesh filter on a DRV pressure control valve of the Common Rail Bosch system protecting the pump against entering of the contaminants in the fuel is the proof of contaminants' presence in the fuel.

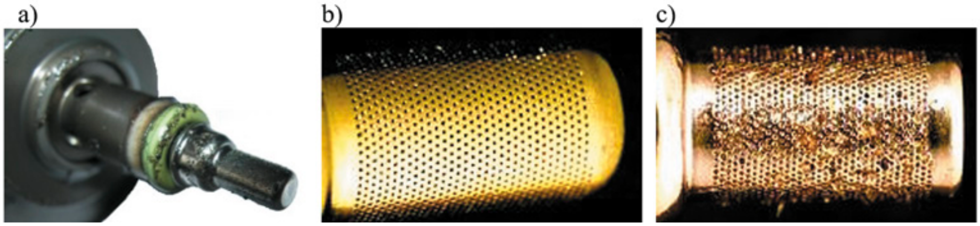

Fig. 32. DRV Bosch Common Rail pressure control valve with a mesh filter (a), new filter view (b), after operation (c) view from a digital microscope [16]

The cause of the injection system components' accelerated wear is insufficient fuel filtration due to delayed filter replacement periods or the use of non-original filters – cheap replacements, whose the filtration efficiency deviates significantly from the ISO standard's requirements – Fig. 33. Then, in the filtered fuel, there is a significant number of contaminant particles with a size of $d_z = (3 \div 15)$ μm. These are the contaminants causing the greatest abrasive connection surfaces wear.

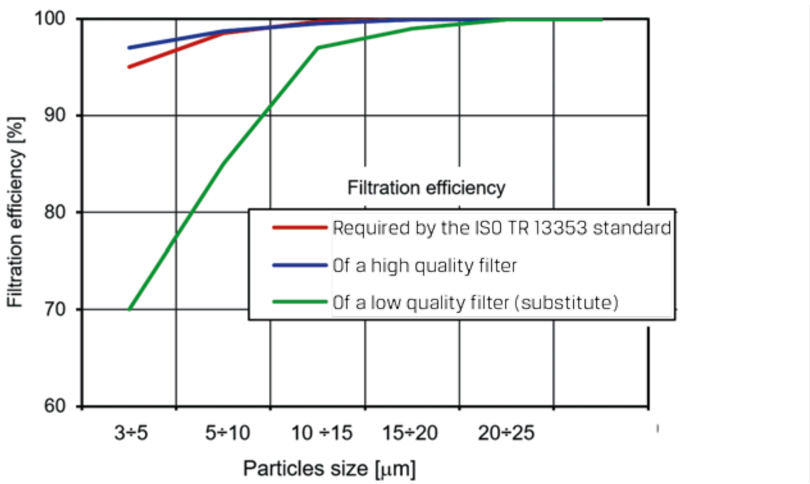

Fig. 33. Filtration efficiency of fuel filters compared to the ISO 13353's requirements [10]

On the fragment of Delphi Nissan Micra 1.5 DCI's valve (soon after the injector dismantling – Fig. 34a), a very large amount of metallic contaminants is clearly visible. The plausible cause of foreign bodies on the valve was the damage to the high pressure pump. While in the Common Rail injector Delphi Ford Mondeo TDCI's valve seat (Fig. 34b), non-metallic contaminants that entered as a result of insufficient fuel filtration are visible.

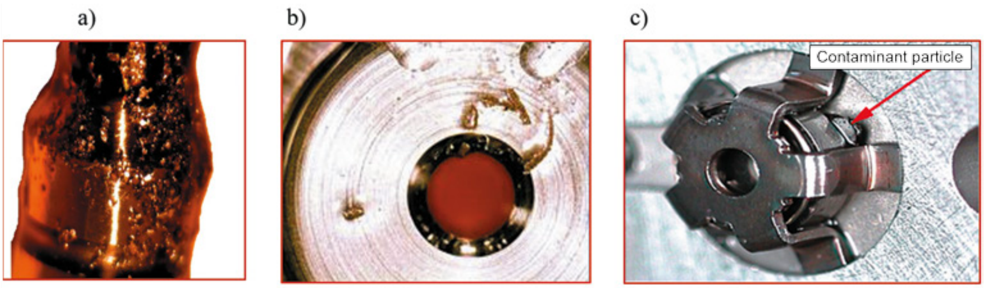

Fig. 34. View of contaminants:
a) on the Delphi Nissan Micra 1.5 DCI's valve: b) in the Common Rail injector Delphi Ford Mondeo TDCI's valve seat [16], c) in the CPI high pressure pump suction valve [7]

Moisture, which is one of the contaminants in the fuel, is above all the cause of corrosive wear in the injection system and the engine (Fig. 35). Its presence in the fuel is the result of insufficient filtration, which is the result of too late filter replacements or the use of low quality non-original filters (Fig. 36a).

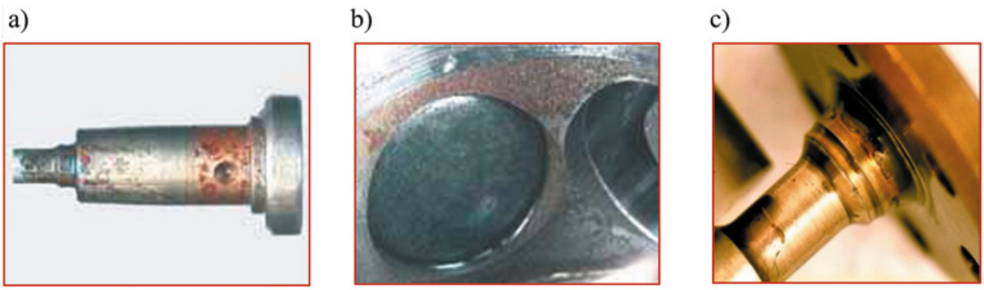

Fig. 35. Corrosive wear of the injection system components at inadequate water filtration: a) injector element corrosion, b) high pressure pump housing [10], c) valve in the Delphi injector [15]

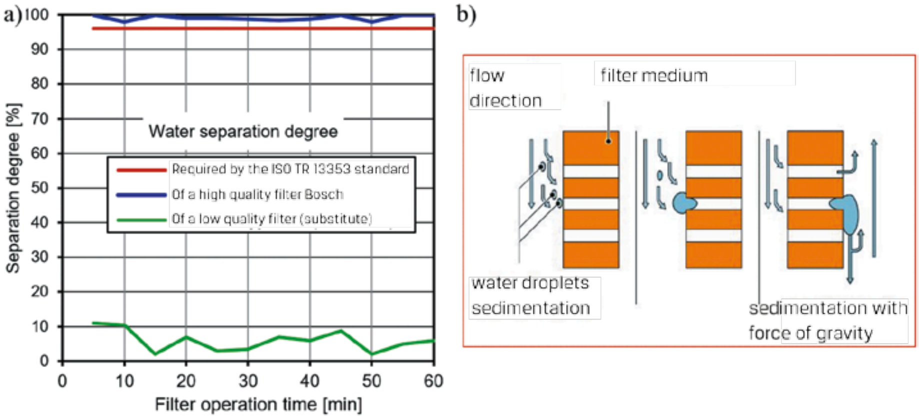

Fig. 36. Water filtration in the fuel filters in terms of the ISO 13353 requirements: a) filtration efficiency, b) separation of water from the fuel as a result of the coalescence effect (water precipitation on the clean filter side) [33]

The easiest method of removing water from engine fuels is gravitational deposition, which is the more effective, the larger the diameters of the water dispersed in the fuel droplets are. Coalescence (Fig. 36b) in a fibrous bed consisting retaining water droplets and depositing on a single fibre, as a result of enlarging the dimensions, is a very effective way to remove water suspended in the fuel. Modern fuel filters are designs characterised with a large number of additional functions. These include sensors and valves controlling pressure and temperature, electrical heaters, heat exchangers, water sensors and water drainage systems (Fig. 37).

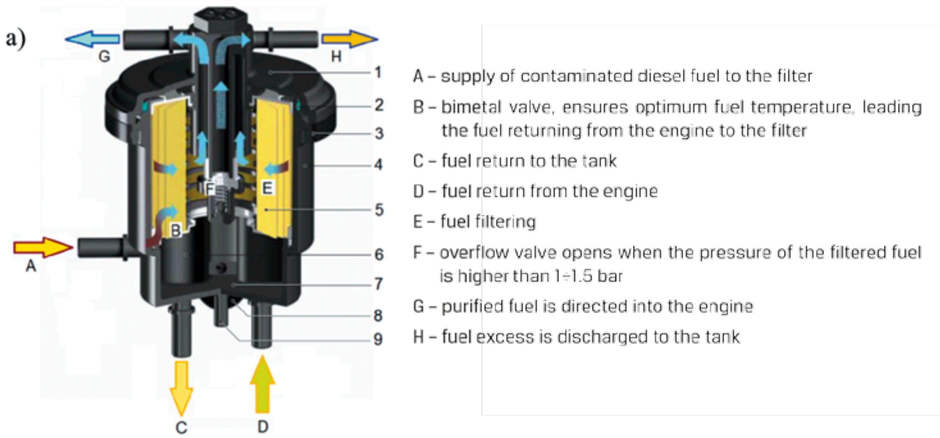

Fig. 37. Fuel filter in the Common Rail system: 1 – plastic filter cover, 2 – o-ring, 3 – metal ring, 4 –plastic filter housing, 5 – filter medium (with folds in a star pattern), 6 – bimetal valve (thermostatic switch), 7 – water settlement tank, 8 – water drain plug, 9 – drainage tube [33]

7. Conclusions

1. Road dust, whose grains are irregular solids with sharp edges and high hardness and maximum sizes of up to (80 ÷ 100) μm, is a common air pollutant harmful to operated mechanical vehicles.

2. The greatest wear is caused by the dust grains of sizes of d_z equal to the minimum h_{min} thickness of an oil layer needed to create a lubricant film between the cooperating surfaces. In typical combustion engine connections, the oil film thickness takes the values within (0 ÷ 50) μm.

3. The dominant wear mechanisms in tribological connections area are the plastic deformations and chasing as well as micro cutting of the surface caused by hard mineral dust grains with sizes comparable with the oil film thickness.

4. All the dust grains cause accelerated wear, although the dust abrasive aggressiveness decreases if the dust grain sizes are below (2 ÷ 5) μm. Such a value is considered to be the top permissible size of dust grains that can be passed through air, fuel oil filters. Larger contaminants grains may get to abrasive connections as a result of filter failures, system leakages or as a result of the use of non-original operating fluid filters.

5. The dust grains with sizes below 1 μm cause the so-called polishing the cylinder bearing surface, as a result of which the oil film formation phenomenon fades, resulting in accelerated wear. The need to remove contaminants with these sizes has resulted in the use of by-pass oil filters.

6. The contaminants in engine fuels cause accelerated wear of injection equipment components in the form of abrasive wear and longitudinal dimples caused by the particles erosion, which results in a decrease in engine power, its uneven operation, an increase in specific fuel consumption and increased toxic compounds emission.

7. In the first period of the air filter operation, dust grains with sizes exceeding the permissible size of (2 ÷ 5) μm several times may enter the engine cylinders, which is due to phenomena in porous barrier during the initial filtration. Then, frequent, unjustified filter element replacement can cause accelerated wear of the P-R-C connection components and thus a decrease in engine power and shortening the overhaul period.

8. The use of original operating fluids filter, where the dominant filter material is filter paper or a composite bed, provides the required filtration efficiency and accuracy, and thus less wear of components and greater systems stability.

The full text of the Article is available in Polish online on the website http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie http://archiwummotoryzacji.pl.

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