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Empirical study of the effect of the air filter on the performance and exhaust emissions of a diesel engine

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The results of an experimental study of the effect of the pressure drop of the air filter pf on the operating parameters and exhaust emissions of a modern CI internal combustion engine of a truck equipped with an electronically controlled power system are presented. The tests were carried out for an air filter with a clean filter cartridge Δp_{f0} = 0.58 kPa and with a cartridge contaminated after a service mileage (about 50 thousand km) Δp_{fD} = 2.024 kPa. In each test, engine performance, exhaust emissions and relative change in emissions were determined: CO, NO_x, HC, CO_2, H_2O. It was found that an increase in the filter resistance pf causes a decrease in the filling degree by 12%, engine useful power by almost 10%, exhaust gas temperature by a maximum of 30°C and an increase in specific fuel consumption by almost 5%. Air filter resistance has no significant effect on NO_x emissions and HC concentration. There is a reduction in H_2O emissions by up to 7%, CO by up to 13% and CO_2 by up to 4%, and an increase in oxygen emissions by 15%, depending on operating conditions.

Key words: *internal combustion engine, air filter pressure drop, engine power, specific fuel consumption, exhaust emissions*

1. Introduction

The basic component of the working medium of any internal combustion engine is air drawn from the atmosphere. The engine's intake system is responsible for supplying ambient air to the engine's cylinders with the right purity [1], in the right quantities and at the right pressure and temperature to ensure proper fuel combustion in the cylinders [2] and minimize wear on engine components [3, 4]. In addition, the intake system, has the task of suppressing the noise caused by the flow of the air stream [5] and forcing the wave phenomena of the flowing air causing resonant charging, which increases the filling pressure p_N in the cylinders, resulting in an increase in engine power [6].

Along with the ambient air, various impurities are drawn into the cylinders of internal combustion engines, mainly mineral dust. About 10–20% of the mass of dust that enters the engine with the air is retained on the walls of the cylinder liner, penetrates between the friction surfaces of the association: piston-piston rings-cylinder (P-PR-C) of the engine, causing abrasive wear [7]. SiO_2 (silica) and Al_2O_3 (alumina) grains are the basic components of mineral dust [8, 9]. The mass share of these two components in the dust reaches up to 95%. Other components in mineral dust: Fe_2O_3, (iron oxide), MgO (manganese oxide), CaO (calcium oxide) [10]. The chemical composition of mineral dust is influenced by: the type of substrate [11], climatic factors (wind, rain, snow, drought, etc.) [12], as well as industrial dust, forest fire dust and volcanic dust [13]. Dusts from the wear of clutch friction linings and pads [14] and car brake discs [15, 16], as well as tires and road surfaces [17], have a large impact on dust emissions into the environment.

Mineral dust grains are lumps with very irregular shapes and sharp edges, usually characterized by high hardness. Silica has a hardness of 7, and alumina has a hardness of 9 according to the 10-point Mohs scale. Abrasive wear of engine components is mainly caused by particles of 1–40 μm [18] with the most damaging particles having a diameter in the range of 1–20 μm [19]. The author of the paper [20] states that about 30% of the pollutants entering the engine cylinders with the air can escape unchanged with the exhaust gas, thus increasing particulate matter (PM) emissions from the engine. The primary way to prevent particulate matter from entering the environment with the exhaust gases is to use special filters [21].

The most dangerous for the two mating components are dust particles, whose diameter dp is equal to the thickness of the oil film h_{min} between the two friction surfaces. In typical internal combustion engine associations, oil film thicknesses take on varying values in the range of h_{min} = = 0.3–50.0 μm [22].

Progressive abrasive wear of the piston-piston rings-cylinder assembly is the cause of significant blowing of fresh charge into the crankcase during compression of the medium. This reduces the mass of the charge, decreases the compression pressure, resulting in a decrease in engine power and an increase in specific fuel consumption [23]. In order to reduce frictional losses and wear in the components of a reciprocating internal combustion engine, wear-resistant coatings are appropriate, which are applied to the sliding surfaces of piston rings and cylinder faces [24]. A decisive role in reducing friction losses in the friction pairs of an internal combustion engine can be achieved by ensuring the continuity and thickness of the oil film. This is realized by properly selecting the shape of the sliding surfaces of the upper as well as the lower sealing ring [25, 26].

It is the responsibility of the air filter to supply the cylinders of an internal combustion engine with air of sufficient purity. For the filtration of air of passenger car engines, which are used in conditions of low concentrations of dust in the air (highways 0.04–10 mg/m^3) [27], single-stage filters with a paper panel cartridge characterized by low dust absorption (200–250 g/m^2), but high (φ = 99.5%) filtration efficiency are used. Trucks, work machinery and special vehicles that are operated under conditions of high dust concentration in the air of 2–10 g/m^3 are equipped with two-stage filters [28]. The first stage of filtration is then a battery of cyclones (multicyclone) [29, 30], and the second, a porous baffle set in series behind it in the form of a cylindrical cartridge made of pleated filter paper with an appropriately sized surface [31–33] or a PowerCore cartridge [34].

An inherent phenomenon during the operation of a baffled air filter is an increase in its pressure drop, resulting from the continuous influx and retention of dust in the filter bed (Fig. 1).

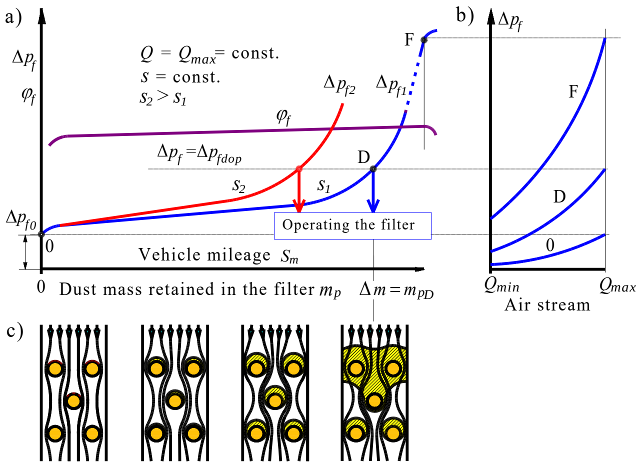

Fig. 1. The essence of baffle filters: a) filtration efficiency φ and pressure drop Δp_f of the air filter with filter media during use (1 – low dust concentration, 2 – high dust concentration), b) aerodynamic characteristics Δp_f = = f(Q) of the air filter, c) changes in the absorptive capacity of the filter bed when loaded with dust

Due to their small thickness, on the order of g_p = 0.4–0.8 mm, filter papers have limited dust absorption. After the dust fills the free spaces between the fibers (depletion of the bed's absorbency), the dust settles on the surface of the bed obstructing the flow of air, which manifests itself in an additional increase in pressure drop.

The intensity of the increase in air filter pressure drop depends on the conditions under which the vehicle is used, including the concentration of dust in the air, the fractional and chemical composition of the dust, and the duration of engine operation. The higher the value of dust concentration in the air drawn into the engine, the faster the filter bed fills with dust and the faster the filter reaches the permissible pressure drop value – Δp_{fdop} (Fig. 1), which has a different value for each engine and air filter mated with it [35, 36]. For the vehicle operator, reaching the value of the filter's permissible resistance determines the need to perform filter maintenance – replacing the filter element with a new one [37, 38].

The value of the permissible pressure drop p_{fdop} of the air filter of a passenger car engine is determined from the condition of a 3% decrease in engine power and is at the level of 2.5–4.0 kPa [39, 40]. For truck engines, the value of Δp_{fdop} is 4–7 kPa [41]. For special-purpose vehicle engines, the Δp_{fdop} value is determined from the condition of a 5% decrease in engine power and is in the range of 9–12 kPa [42, 43]. Operation of the vehicle after the Δp_{fdop} value of the air filter is possible, but not advisable.

After the Δp_{fdop} value is reached, the air filter continues to undergo the filtration process, which is characterized by an increasing increase in pressure drop while maintaining a high value of filtration efficiency. This stage of air filter operation creates two unfavorable phenomena for the engine: accelerated wear of its components and excessive power loss. Firstly, the air filter flow resistance, which is significantly increased above Δp_{fdop}, and the high air flow velocity in the filter bed, can cause "secondary emission" of dust grains. This is the detachment of dust grains from agglomerates and their movement toward the filter outlet. This phenomenon results in an increased number of large dust grains (about 10–25 μm) in the air downstream of the filter and reduced efficiency, resulting in accelerated wear of P-PR-C association elements.

Operation of the air filter after the Δp_{fdop} value is reached is not advisable due to the adverse effect of filter pressure drop on engine operation and performance and exhaust emissions. Increasing air filter pressure drop during operation lowers the value of mass air flow, which can cause a decrease in the engine's fresh charge. Deficiency of oxygen in the fuel-air mixture is the cause of disruption of the mixture preparation and combustion process, prevents the combustion of an adequate mass of fuel, which is the direct cause of a decrease in engine power (torque) an increase in specific fuel consumption and an increase in exhaust smoke [44]. These phenomena increase in intensity when the permissible resistance value is exceeded. Hence the need to replace the filter element when a certain pressure drop Δp_{fdop} is reached. The operation of an air filter is a technical compromise between pressure drop (car mileage), separation efficiency and accuracy, and engine wear and durability, as well as facility reliability [45, 46].

The primary fuel of modern compression-ignition engines is diesel fuel. Due to the depletion of fossil fuels, especially oil, climate change, economic problems, population growth and energy demand, intensive research work is being carried out to obtain alternative fuels to diesel [47–52]. For this reason, research on compression-ignition engines fueled by fuel blends as an alternative to diesel fuel is gaining great importance in the direction of performance and emissions. In addition, during the study of engines with alternative fuels, the influence of various design and operational parameters is evaluated in the direction of reducing exhaust emissions. For example, in [47], a study was conducted on a common-rail diesel engine to evaluate the effect of a diesel-butanol blend on particulate matter (PM) emissions using a pilot injection strategy. The addition of n-butanol can improve the mixing of fuel and oxidizer and lower the average temperature in the combustion chamber and consequently reduce NO_x emissions (up to 25%) and PM emissions (up to 69%). A study [48] examined the suitability of diesel-biodiesel and diesel-biodiesel-hexanol fuel blends as alternatives to diesel fuel. The results showed that the most suitable alternative fuel to diesel was a binary diesel-biodiesel fuel blend. On the other hand, the paper [49] investigated the effect of cyclohexanol mixed with diesel fuel at different volume ratios on the emissions performance of a Diesel engine at different degrees of exhaust gas recirculation and injection times. The cyclohexanol-diesel mixture significantly reduced particulate matter (PM) and volumetric concentration at the expense of higher NO_x emissions. Cyclohexanol, which is derived from biomass, has been shown to be a promising alternative fuel for diesel engines. The paper [50] presents the effect of the heating time of a catalyst-covered glow plug on the exhaust emissions from a compression-ignition engine. Placing the catalyst in the combustion chamber, the place where the combustion process takes place, allows reducing emissions of: carbon monoxide, hydrocarbons and particulate matter. An improvement in the efficiency of oxidation of exhaust gas components was observed with an increase in the heating time of the glow plug. The authors of the paper [51] presented an experimental study of a common-rail diesel engine fueled by diesel fuel and a mixture of diesel and alcohol (butanol and hexanol). Engine performance and emissions of NO_x, CO, HC and soot were studied for five different ambient pressures (0.12; 0.1; 0.08; 0.07; 0.06 MPa) and for two loads (average effective pressure p_e = 0.45 MPa and 0.55 MPa). Adding butanol and hexanol (20% and 40% by volume) to diesel fuel, significantly reduced particulate matter and CO emissions, especially when the ambient pressure was below 0.1 MPa. However, the combustion of alcohol-diesel mixtures resulted in higher NO_x emissions than the combustion of diesel under the same conditions, which is also confirmed by other studies reported in [52, 53].

From the above analysis, the air filter pressure drop, which increases its value during operation and has a significant impact on engine performance and exhaust emissions, is not taken into account during experimental testing of engines. In addition, the authors of the test results do not state whether the experiment was performed with or without the presence of an air filter in the intake system.

The available literature does not provide enough information regarding the effect of air filter pressure drop on engine performance. There is mainly a lack of information regarding changes in engine emissions. The authors studied the description of studies of the effect of air filter pressure drop on the operation of naturally aspirated internal combustion engines: carburetor and diesel engines, but equipped with a classic injection system with an in-line piston (sectional) injection pump [54–59]. Today, engines of this type are not used in motor vehicles. The paper [54] presents the effect of three values of air filter flow resistance (Δp_f = 2.3; 6 and 12 kPa at n_N = 2800 rpm) on the characteristics of: filling ratio η_υ = f(n), power N_e = f(n) and torque M_o = f(n) and specific fuel consumption g_e = = f(n) of a naturally aspirated (V_{ss} = 6,84 dm^3) Diesel engine with a classical injection system. Operation of the engine in the speed range n = 1200–2800 rpm shifts the characteristics of η_υ = f(n), power N_e = f(n) and M_o = f(n) almost in parallel towards lower values of η_υ, N_e, M_o, and g_e = f(n) towards higher values of g_e. An increase in air filter pressure drop from 2.3 kPa to 12 kPa during engine operation at n = 2800 rpm and 100% load, results in a decrease in: fill factor η_υ by 25.7%, power N_e by 7.16% and increase in g_e by 8.49%.

The results of a study of the effect of air filter pressure drop Δp_f on the external characteristics of N_e effective power and specific fuel consumption ge of a special vehicle Diesel engine are presented in [55]. An increase in air filter pressure drop in the range Δp_f = 6–30.7 kPa causes a significant decrease in engine power and an increase in specific fuel consumption. There is a parallel shift of N_e power characteristics towards lower N_e speed power values. An increase in filter pressure drop causes a shift in the characteristics of specific fuel consumption g_e toward higher values of g_e and lower rotational speeds. For pressure drop Δp_f = 26.7 kPa, the decreases in N_e power take on values of: 11.75% at 2000 rpm and 20.6% at n = 1400 rpm and 32.7% for 1200 rpm.

The authors of the paper [56] presented an experimental study of the effect of air filter pressure drop on the fill factor and smoke opacity of a Diesel engine used to power a truck. Air filter pressure drop was modeled for four technical states in the range of Δp_f = 3.1–24.7 kPa at an engine speed of n = 2400 rpm. For an air filter with a clean filter element (Δp_f = 3.1 kPa), the fill factor has a value of $\eta_\upsilon \approx$ $\approx$ 1.02. For subsequent technical states of the air filter (increase in pressure drop Δp_f), the fill factor takes on smaller and smaller values, respectively: $\eta_\upsilon \approx$ 0.90; 0.81; 0.75. For the same values of Δp_f, the smoke opacity (light absorption coefficient) assumes the following values, respectively: k = = 0.42 m^{-1}, k = 0.49 m^{-1}, k = 0.62 m^{-1}, k = 0.81 m^{-1}. The obtained smoke opacity values do not exceed the permissible value, which for the T359E engine is k_{max} = 3.0 m^{-1}.

The effect of baffle filter pressure drop on the performance characteristics of a special vehicle's compression-ignition engine was presented in [57]. The effect of two filters differing in pressure drop was studied: an original air filter (Δp_f = 13.2 kPa) and an upgraded filter (Δp_f = 4.9 kPa). The engine with the upgraded filter was fed by an injection pump with an increased fuel dose of about 7%. In the latter variant, a significant (more than 2% for n = 1600 rpm and more than 10% for the n = 2200–2600 rpm range) increase in horsepower and torque was obtained compared to the basic filter variant.

Yang et al [58] studied the effects of two different air filter designs with different pressure drop (A – standard filter, B – upgraded filter with lower pressure drop), on effective power, torque, specific fuel consumption, exhaust smoke, oil temperature, engine exhaust temperature. The engine operating without an air filter obtained the highest power and torque and the lowest fuel consumption. Running the engine sequentially with filter B and A shifted the N_e = f(n) and M_o = f(n) characteristics almost in parallel toward smaller values, and the g_e = f(n) characteristics toward larger values, over the entire engine speed range. As expected, the engine operating with a type B air filter (lower pressure drop) achieved increases in torque and power, respectively: 1.6% and 1.1%, and a decrease in fuel consumption of 1.5% with respect to operation of the engine with a Type A air filter The maximum value of the smoke opacity (light absorption coefficient) increases with increasing load, and during operation of the engine without an air filter, with a Type A and Type B air filter is: k = 1.7; 2.36 and 2.0 m^{-1}, respectively. After replacing the Type A air filter with a Type B filter, a reduction in smoke opacity of 11% was obtained.

Plotnikov et al. [59] numerically studied the effective parameters of a turbocharged diesel engine by changing the length of the inlet duct L and the internal diameter D mm. Increasing the diameter to D = 250–330 mm leads to a decrease in pressure drop, and an increase in the fill factor by an average of 0.5%. As a result, engine power increased by 0.7% and specific fuel consumption decreased in the range of 0.50–0.75%.

Abdullah et al [60] evaluated the fuel consumption and exhaust emissions of a carburetor engine as the intake system pressure drop increased. The engine was operated with and without an air filter. The tests were performed while the engine was running with and without an air filter. In the speed range of 1500–2500 rpm during engine operation at a constant load, hourly fuel consumption with an air filter increases by 49.6%, and without an air filter by 35.2%. In the absence of an air filter, CO_2 and NO_x concentrations in the exhaust gas at n = 2500 rpm are 22% and 17% higher, respectively, than when the engine is operated with an air filter.

Shannak et al. [61] studied the exhaust emissions of a gasoline engine as a function of the pressure drop of the intake system, the value of which was modeled by using different diameters of the intake pipes of the ambient air. The study was carried out by varying the engine speed in the range of n = 1000–4000 rpm. As flow resistance decreases (intake pipe diameter increases), hydrocarbon (HC) and carbon monoxide (CO) emissions decrease, while carbon dioxide (CO_2) and oxygen (O_2) remain constant.

There are only a few papers in the literature addressing the effect of air filter pressure drop on engine performance and exhaust emissions [62–65]. Thomas et al [62] studied the effect of air filter pressure drop on changes in engine emissions of three modern trucks. The vehicles were powered by turbocharged diesel engines of different displacement and design. The results showed that a change in the condition of the air filter (an increase in pressure drop) does not significantly affect the performance and exhaust emissions of modern Diesel engines. Example test results for a Volkswagen Jetta TDI 2.0 L car with a turbocharged inline four-cylinder engine, with a diesel particulate filter (DPF) and LNT emission system are shown in Fig. 2. An increase in air filter pressure drop from 1.7 kPa to 4.1 kPa and then to 6.7 kPa does not cause significant changes in CO_2 and specific fuel consumption, while there is a systematic decrease (more than 90%) in NO_x emissions.

The effect of panel pressure drop (filter paper) of the air filter after the vehicle run on selected engine and vehicle parameters: power and specific fuel consumption, exhaust emissions and vehicle dynamics, is presented in [63]. Measurements were carried out on a chassis dynamometer using two vehicles, where the power unit was a turbocharged compression-ignition engine with air cooling, and in two vehicles with a SI engine, one naturally aspirated and the other turbocharged and air-cooled.

The results indicate a relatively small effect of air filter pressure drop on the studied parameters of turbocharged engines, where a decrease in engine power in the range of 2–3% was registered. In contrast, the power loss of a naturally aspirated engine with ZI was twice as large – 6.2% [63].

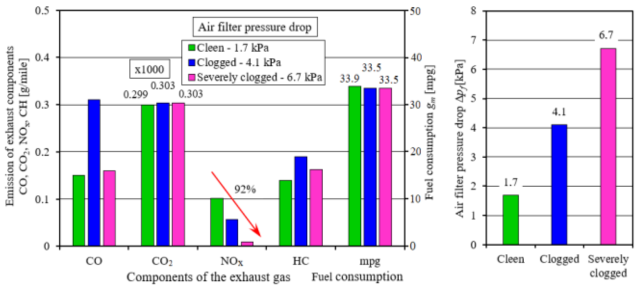

Fig. 2. The effect of an increase in baffled air filter flow resistance on emissions of exhaust components: CO, CO_2, NO_x and fuel consumption of the engine of a Dodge Ram 2500 Truck 6.7 L. Figure made by the authors based on data from the paper [62]

The paper [64] presents, in the speed range of n = 1000–2100 rpm, the results of a study of the effect of three technical states of the air filter (different pressure drop of the filter element) on the performance parameters (power, hourly and specific fuel consumption, boost pressure and exhaust gas temperature) of a modern Diesel truck internal combustion engine. It is shown that an increase in air filter resistance causes a decrease in power (9.31%), hourly fuel consumption (7.87%), exhaust gas temperature (5.1%) and boost pressure (3.11%). At the same time, there is an increase in specific fuel consumption (2.52%), smoke opacity, which does not exceed the permissible values resulting from the technical conditions for vehicle approval.

The above analysis confirmed that the air filter in the engine intake system is a device that ensures the delivery of high-purity air to the cylinders, which minimizes the wear of components working in frictional associations. An undesirable effect of a porous baffle air filter is the increase in pressure drop during its use, which results from the accumulation of dust inside the baffle. This results in a decrease in boost pressure in the intake system, resulting in a decrease in the effective performance of the engine and an increase in exhaust emissions. The negative effects worsen as the value of pressure drop increases above the value of the permissible resistance Δp_{fdop}. Hence the need to replace the filter element with a new one. Determining the value of pressure drop at which this should be done is the subject of many studies. The analysis shows that the results of studies from the 1970s, which show the effect of air filter pressure drop on the performance of carburetor internal combustion engines and diesel engines equipped with a classic injection system with an in-line piston injection pump, cannot be used to assess the effect of air filter pressure drop on the performance of modern engines. Fuel dosage control in old-style engines was not coupled to the technical condition (pressure drop) of the intake system. The results of these studies are now of limited use to vehicle manufacturers and users, as motor vehicle technology has changed and developed significantly.

Mechanical power systems (carburetor, in-line injection pump) have been eliminated from the engine's fuel supply system and replaced with multipoint, direct, electronically controlled fuel injection. Mechanical single-parameter control has been replaced by electronic multi-parameter control, which takes into account a number of operating parameters of the engine as well as the vehicle itself. The CI engine as well as the SI engine are equipped with a turbocharger and a charge air chiller. The engine ECU controls all the quantities that affect the value of the torque generated by the engine, while meeting the requirements in the area of exhaust emissions and fuel consumption throughout the life of the vehicle. The analysis shows that the available literature practically does not present the results of experimental studies of the influence of the pressure drop of the intake system, including the air filter, on the performance of a modern internal combustion engine, and in particular on the composition and changes in exhaust emissions. Studies of this type are carried out by experimental method using an engine dynamometer. These are costly and labor-intensive studies, which explains the scant number of available results. However, despite the high cost of conducting such research, it is the most reliable research method at the moment.

Therefore, the purpose of this paper is to try to partially fill this gap and determine, by conducting experimental tests on an engine dynamometer, the quantitative and qualitative effects of air filter pressure drop on the performance parameters (fill factor, effective power, specific fuel consumption), and in particular on exhaust emissions, of a modern CI engine with electronic fuel injection control, which is applied to the drive of truck tractors. This problem is particularly important, due to the fact that modern engines with CI use a multi-parameter fuel injection and dosage strategy aimed at minimizing exhaust smoke and preventing an increase in emissions of toxic exhaust components, rather than at obtaining maximum power. The obtained test results can be used by designers to appropriately select an air filter for the engine and program the permissive resistance sensor to such a value Δp_f, at which the engine obtains an acceptable value of smoke opacity, rather than a fixed decrease in power.

2. Experimental study of the engine

2.1. Purpose and object of the study

The purpose of the study was to experimentally evaluate the effect of the increased in-service air filter pressure drop Δp_f on the useful parameters of the engine of a modern truck – useful power, hourly and specific fuel consumption, charge air pressure, exhaust gas temperature and smoke, as well as changes in the concentration and emission of the main components of the exhaust gas: carbon dioxide, carbon monoxide, oxides of nitrogen as the sum of NO, NO_2 and N_2O, oxygen and water vapor treated as a greenhouse gas.

The test object was an inline six-cylinder compression-ignition engine with direct fuel injection and electronically controlled injectors. This is a Volvo D13C460 EURO V EEV engine with a maximum power of 338 kW, which is the power unit of a Volvo FH13 truck tractor. Prior to testing, the engine was removed from the vehicle and mounted on a dynamometer bench. The technical condition of the engine up to the time of the tests was determined by its total operating time, which amounted to 11,800 hours and a mileage of 773,800 kilometers. The change in engine power and torque is shown in the external factory characteristics (Fig. 3) [65]. The tested engine met the requirements of the EURO V standard.

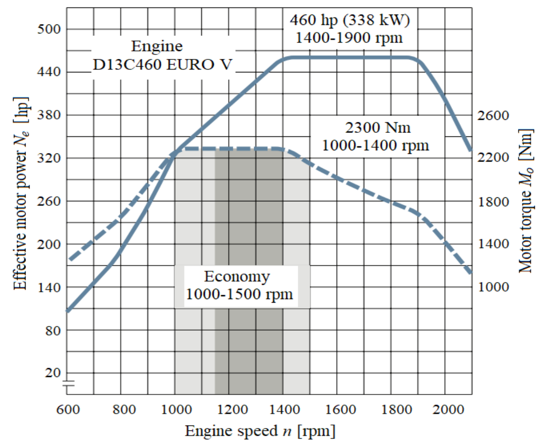

Fig. 3. Variation of power and torque on the external characteristics of the VOVLO DC13C460 motor (338 kW) given by the manufacturer [65]

The economical operation of the engine is between 1000–1500 rpm, which corresponds to the range of maximum torque, which is kept constant at around 2300 Nm in this range. The speed range at which the engine reaches its maximum power of 338 kW is 1400–1900 rpm.

The intake air flow to the engine from the environment is provided by an air supply system (Fig. 4), where its first element is an air intake located on the right side of the cab at its highest height.

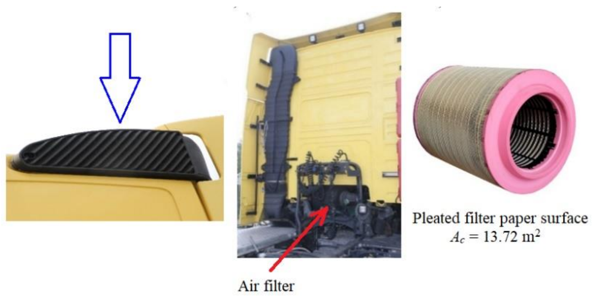

Fig. 4. Air supply system for the engine of a Volvo FH13 truck tractor: a) air intake, b) general view of the air supply system, c) paper filter cartridge

The air supply from the air intake to the filter is provided by a vertical intake duct of rectangular cross-section located outside the rear wall of the cab. Adequate purity of the inlet air to the engine is provided by a baffled air filter. Its filter element is a pleated filter paper cartridge with an active area A_c = 13.72 m^2 shaped into a cylinder. On the outlet line from the air filter there is a sensor for signaling the permissible flow resistance Δp_{fdop}, the value of which is set at Δp_{fdop} = 4.8–5.0 kPa. Completing the intake system is a turbocharger and a charge air cooler, which operates in an "air-to-air" system.

During the tests, commercial diesel fuel was used to power the engine, so before the tests, tests were performed on its basic parameters, which are shown in Table 1. The various parameters were determined during the tests in a specialized laboratory in accordance with applicable standards.

2.2. Methodology and conditions of engine testing

The experiment was carried out using a dynamometer station, where the engine was loaded with a water brake of the Zöllner PS1-3812/AE type. Measuring instruments, whose technical characteristics are shown in Table 2, were used to measure individual engine operating parameters.

The composition of the exhaust gas was measured using Fourier Transform Infrared Spectroscopy (FTIR) with an Atmos FIR analyzer operating on a 180°C hot sample. the configuration of the instrument used during the tests made it possible to measure several components of the exhaust gas: NO, NO_2, N_2O, HC, CO, CO_2, O_2 and H_2O. The measured values were brought to normal conditions (p_n = = 101325 Pa, T_n = 273.15°C) [66].

The experiment was conducted by varying the engine speed in increments and keeping the engine at full load – the maximum swing of the accelerator pedal. Once the thermal equilibrium conditions of the engine were established, the fuel dosage was adjusted to achieve full engine load. Then, controlling the water brake accordingly, the lowest (n = 1000 rpm) possible speed at which engine operation was still steady was set. After the engine operating conditions stabilized, measurements were taken of the various engine operating parameters. Then the engine load was reduced so as to achieve an increase in speed, and the next higher speed was established (at an interval of 100 rpm), and measurements were taken again. According to the above methodology, engine performance was measured for rotational speeds in the range of 1000–2100 rpm.

During the tests, For each rotational speed in this range, the engine's operating parameters and the parameters of the air flow supplied to the engine, as well as the composition and opacity of the exhaust gas, were measured directly:

- engine speed, n [rpm]
- engine torque, M_o [Nm]
- hourly fuel consumption, G_e [kg/h]
- engine air demand, Q_s [m^3/h]
- air pressures before p_1 and after the air filter p_2 [kPa]
- charge air pressure, p_d [kPa]
- exhaust gas temperature, t_s [°C]
- exhaust gas opacity – light absorption coefficient (absorption), k [m^{-1}]
- concentration of exhaust gas components: HC, NO, NO_2, N_2O, CO, CO_2, O_2, H_2O.

Based on the directly measured values of engine operating parameters, the following parameters were determined indirectly:

- effective engine power, N_e [kW]
- specific fuel consumption, g_e [g/(kWh)]
- mass air demand of the engine $\dot{m}_{rz}$ [kg/h]
- air filter pressure drop Δp_f [kPa]
- specific emissions of exhaust components: HC, NO_x, CO, CO_2, O_2, H_2O
- relative change in: effective engine power, specific air consumption and emissions of exhaust components
- filling factor η_υ.

Emissions of the various components of the exhaust gas were determined in accordance with the requirements of [36]. NO_x concentration was determined as the sum of NO + NO_2 + N_2O components. The relative change in emissions of the individual components of the engine's exhaust gas was determined as the ratio of the difference in emissions obtained for the clean "Clean" filter and the filter with reduced airflow, which caused the technical condition of the filter labeled "Dirty," relative to the emissions for the clean "Clean" filter.

During the study, the effect of the technical condition of the air filter (the effect of pressure drop Δ_{pf}) on water vapor emissions was also evaluated. Water vapor is the most important occurring greenhouse gas on Earth. Data from satellites, weather balloons and ground measurements confirm that as the climate warms, the mass of atmospheric water vapor increases. The Sixth IPCC Report states that the total mass of atmospheric water vapor is increasing by 1–2% per decade [67].

In order to eliminate coarse errors that could lead to incorrect conclusions, all tests were repeated twice.

During the tests, the engine's operation was continuously monitored by using the NAVIGATOR TXTs diagnostic interface with IDC 5 TRUCK software. The technical characteristics of the test apparatus used during the tests are given in Table 2.

Table 1. Basic parameters of diesel fuel used to power the engine during the tests

Parameters	Units	Results	Limits	Standard of test method	Device name
Density at 15°C	kg/m^3	828.7	<820; 845>	PN-EN ISO 12185:2002	Densitometer DMA™ 35
Kinematic viscosity at 40°C	mm^2/s	2.84	<2.0; 4.5>	PN-EN ISO 3104:2021-03	Pinkiewicz viscosity meter
Acid number	mg/g KOH	0.06	no requirement	PN-EN ISO 660:2021-03	702 SM Titrino
Cetane number	–	54.5	≥ 51.0	**	IroxDiesel
Cetane index	–	57.5	≥ 46.0	**	
Oxidative stability	min	68.9	no requirement	PN-EN 14112:2021-05	PetroOxy
Flash point	°C	67.5	≥ 55.0	PN-EN ISO 2719:2016-08	Pensky-Martens
Cloud point	°C	–9.2	no requirement	PN-EN ISO 3015:2019-06	ISL CPP 97-2
Cold filter plugging point	°C	–26.7	≤ 0*	PN-EN 116:2015-09	ISL CPP 97-2
Total polyaromatics	% (m/m)	1.73	≤ 8.0	**	IroxDiesel
FAME content	%	5.0	≤ 7.0	**	

* Requirement for summer period gas-oil auto
** The device does not have a standard for the test method; however, there is a correlation of test results performed according to the standard PN-EN ISO 5165:2021-02

Table 2. List of investigation equipment used during investigation

No.	Name of device/measured quantity	Type	Range	Accuracy
1.	Water dynamometer • torque – M_o • rotated speed – n	Zöllner PS1-3812/AE	M_o = 0–7000 Nm n = 0–3000 rpm N_e = 0–1250 kW	± 1 Nm ± 1 rpm ± 1 kW
2.	Fuel weight-meter (diesel) – G_e	AVL 733S Fuel Balance	0–200 kg/h	± 0.005 kg/h
3.	Smoke concentration – extinction coefficient of light radiation – k	AVL Opacimeter 4390	0.001–10.0 m^{-1}	± 0.002 m^{-1}
4.	Exhaust analyser–measuring of toxic elements concentration in exhaust gases • carbon dioxide (CO_2) • carbon monoxide (CO) • nitrogen oxides (NO) • nitrogen diooxide (NO_2) • dinitrogen oxide (N_2O) • oxygen (O_2) • steam (H_2O)	Atmos FIR emissions monitoring FTIR systems	CO_2 (0.01–23)% CO (1.0–11,000) ppm NO (1.0–6000) ppm NO_2 (1.0–300) ppm N_2O (0.5–50) ppm O_2 (0.1–21)% H_2O (0.25–25)%	± 0.1% measured quantity
5.	Thermocouple—measuring of exhaust temperature – t_s	NiCr–NiAl (type K)	–50–1100°C	± 1°C
6.	Mass air consumption – Q_s	SensyMaster FMT430 Thermal Mass Flowmeter	100–6000 m^3/h	± 1.0 m^3/h

During the tests presented in this paper, the influence of two, differing pressure drop, technical states of the air filter: a "Clean" filter element and after a service run "Dirty", on the external characteristics of the Volvo D13C460 EURO V engine was determined. In each case, the same parameters characterizing engine operation were measured.

At an engine speed of n = 1900 rpm, the air filter pressure drop obtained the following values:

- "Clean" condition – air filter with "Clean", brand new, paper insert, Δp_{f0} = 0.580 kPa
- "Dirty" condition – air filter after a service mileage, Δp_{fD} = 2.024 kPa. This condition corresponds to a tractor-trailer mileage of approximately 50,000 km, under long-distance transport conditions.

2.3. Results of inlet system flow tests

The results of engine tests where air filters having different flow resistance values were placed successively in the intake system are presented in the form of characteristics: effective power N_e = f(n), specific fuel consumption g_e = f(n), hourly fuel consumption G_e = f(n), boost pressure p_d = f(n), air flow Q_s = f(n), flow resistance Δp_f = f(n), exhaust gas temperature t_s = f(n), smoke index k = f(n), GAS = f(n) and relative change in emissions of exhaust components (Fig. 5–27).

Figure 5 shows, depending on the speed n of the Volvo engine, the change in the flow resistance of two technical states of the air filter ("Clean", "Dirty") and the effect of the technical states "Clean", "Dirty" on the engine's air demand.

The tests and analysis of the results were performed in the range of rotational speeds that are used during the operation of a vehicle equipped with this type of engine. It was found that an increase in engine speed in the range of n = = 1000–2100 rpm causes an increase in the flow resistance of the air filter, regardless of the degree of contamination of the cartridge. The increase in flow resistance occurs until the engine speed reaches n = 1900 rpm. This is related to the achievement of maximum air demand by the engine and maximum useful power (Fig. 5). The increase in engine speed above n = 1900 rpm causes a decrease in the flow resistance of the air filter, which is due to the decrease in air flow Q_s at this time.

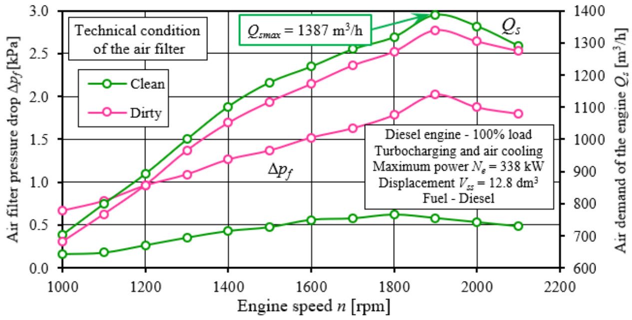

Fig. 5. Change in the flow resistance of two different technical states of the air filter ("Clean", "Dirty") and the change in the air demand of the Volvo D13C460 EURO V engine depending on the speed n

Changing the state of the filter from „Clean” to „Dirty” resulted in a more than threefold increase in the pressure drop of the filter compared to a filter with a „Clean” cartridge. At n = 1900 rpm, the „Dirty” filter reaches a maximum value of 2.024 kPa, when the manufacturer's set permissible pressure drop of 4.8–5.0 kPa is checked at engine speed n = 1900 rpm and engine operating temperature. Exceeding the set value of permissible pressure drop of the filter means the necessity of carrying out servicing consisting in replacing the filter cartridge with a new one – „Clean”. Failure to perform this operation does not exclude the filter and the vehicle from further use. Continued operation of the air filter is possible, as the filtration process in the bed continues, characterized by high efficiency (φ_w = = 99.9%), but also by a higher increase in pressure drop. In the air behind the filter, dust grains begin to appear in larger quantities and with increasingly larger sizes, reaching d_{pmax} = 15–20 μm. This phenomenon is caused by the high negative pressure (pressure drop) created behind the filter and the high velocity of the air flow in the spaces between the fibers of the filter bed, resulting in the local detachment of dust grains from the agglomerates formed on the fibers and their migration towards the outlet.

If a certain resistance limit is exceeded, mechanical destruction (rupture) of the filter material of the filter insert may occur, resulting in more and larger dust grains entering the engine cylinders, which will result in accelerated wear of the T-PR-C elements.

During testing using the „Dirty” filter, an acceptable pressure drop value was not achieved. The low (0.604 kPa) pressure drop value of the new „Clean” air filter is the result of the paper's filter area, which guarantees a low air flow velocity through the paper surface, referred to in the literature as the maximum filtration velocity Fmax and calculated from the relationship:

$$\upsilon_{Fmax} = \frac{Q_{smax}}{3600 \cdot A_c} \text{ [m/s]} \tag{1}$$

where: Q_{smax} – the maximum air demand of the engine [m^3/h], A_c – the active area of the filter media [m^2].

For the maximum air demand Q_{smax} = 1387 m^3/h (Fig. 5) and for the filter area A_c = 13.72 m^2, according to relation (1), the filtration velocity in the tested filter assumes the value υ_{Fmax} = 0.0281 m/s, which is 50% less than the permissible value of the filtration velocity υ_{Fmax} = 0.06 m/s, which is assumed during the design work of air filters [44]. The low value of the filtration velocity guarantees a long interval between air filter maintenance – replacements of the paper filter element.

In the case of the engine under test, the air demand Q_s, regardless of the technical condition of the air filter, increases rapidly in value until the engine reaches a speed of n = 1900 rpm, at which it reaches a maximum, and then decreases (Fig. 5). The use of an air filter with higher pressure drop) shifts the characteristics of Q_s = f(n) almost in parallel towards the lower values of the engine's air demand Q_s. At n = 1900 rpm, the drop in Q_s is 3.39%.

Figure 6 shows the variation of the fill factor η_υ = (n) and charge air pressure p_d = (n) in the engine intake manifold for two technical states of the air filter: „Clean”, „Dirty”. The fill factor was defined by the relation:

$$\eta_\upsilon = \frac{\dot{m}_{rz}}{\dot{m}_t} \tag{2}$$

where: $\dot{m}_{rz}$ – average actual mass flow rate of the air supplied to the engine cylinders at specified operating conditions and for a sufficiently long time interval to eliminate the influence of pressure pulsations in the intake duct, $\dot{m}_t$ – theoretical mass flow rate of the air supplied to the engine cylinders at specified operating conditions.

The actual mass flow rate of the air supplied to the engine cylinders was determined from the measured engine air demand Q_s and the assumed air density ρ_p. The mass theoretical flow rate of the air supplied to the engine cylinders was determined from the relation:

$$\dot{m}_t = Q_{st} \cdot \rho_p \tag{3}$$

where: Q_{st} – the engine's theoretical air requirements, ρ_p – the air density at ambient conditions. The theoretical air requirements Q_{st} were determined from the relationship:

$$Q_{st} = \frac{V_{ss} \cdot n \cdot \eta_\upsilon \cdot k_p \cdot 60}{1000 \cdot \kappa} \text{ [m}^3\text{/h]} \tag{4}$$

where: V_{ss} – engine displacement [dm^3], n – engine speed [rpm], η_υ – filling factor, κ – stroke number factor (2 – for four-stroke engines, 1 – for two-stroke engines), k_p – flushing factor.

Due to the constant angle of coverage – valve co-opening, the flushing coefficient was assumed at a constant level of k_p = 1.

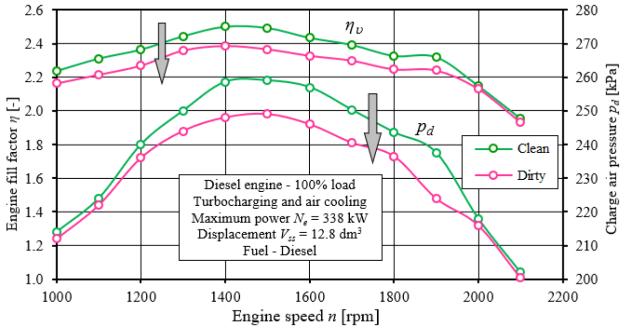

Fig. 6. Change in engine fill factor η_υ and charge air pressure p_d in the intake manifold of the VOVLO DC13C460 engine depending on engine speed n caused by two technical states of the air filter: "Clean", "Dirty"

Independent of the condition of the air filter ("Clean", "Dirty"), the engine boost pressure increases quite sharply in value as the engine speed increases. In the range n = = 1400–1500 rpm, it reaches maximum values (about 260 kPa), after which it steadily decreases. As the engine speed increases, regardless of the condition of the filter, the engine boost pressure increases quite sharply, and in the range n = 1400–1500 rpm it reaches maximum values – up to 260 kPa, after which it systematically decreases. At n = 1600 rpm, the decrease in boost pressure p_d, caused by the increase in air filter flow resistance resulting from the transition from the "Clean" to the "Dirty" state in relation to the value of the resistance of the new "Clean" filter, reaches a value of 4.28%.

The research presented in [68] clearly shows that engine boost pressure has a significant effect on engine performance, the emission of individual exhaust components and the combustion characteristics of the engine regardless of the fuel used – diesel, biofuels. Studies have shown that lowering the boost pressure increases the ignition delay, which has a negative impact on engine performance characteristics. As a consequence, a reduction in boost pressure results in the maximum cylinder pressure and maximum heat release rate moving away from top dead centre (TDC). On the other hand, increasing boost reduces the ignition delay and the heat release phase of the initial combustion phase, thus intensifying the diffusion combustion phase.

Shown in Fig. 6, the changes in the fill factor η_υ of the engine with the increase of the engine speed, indicate that regardless of the technical condition of the filter ("Clean", "Dirty"), the fill factor η_υ of the engine increases and in the range of n = 1400–1500 rpm reaches a maximum value, respectively: η_υ = 2.38 and η_υ = 2.5, after which it steadily decreases to a value of about η_υ = 1.8. As the flow resistance Δp_f increases, the "Dirty" state of the air filter filling characteristics η_υ = (n), in the speed range n = 1000–1900 rpm, is shifted almost parallel towards smaller values.

An increase in the flow resistance of the air filter from the value Δp_{f0} = 0.580 kPa ("Clean" state) to Δp_{fD} = 2.024 kPa ("Dirty" state) results in a decrease in the maximum value of the fill factor from η_υ = 2.5 to η_υ = 2.39, i.e. by about 4.5%.

2.4. Results of tests of effective engine parameters

Figure 7 shows the characteristics of effective power N_e = f(n) and specific fuel consumption g_e = f(n) of the VOVLO DC13C460 engine for the technical states of the air filter ("Clean", "Dirty").

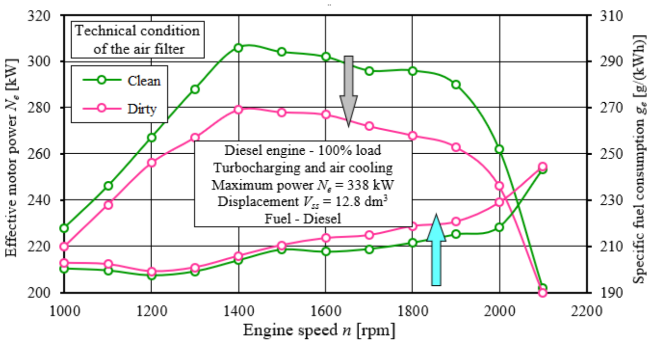

Fig. 7. Variation of effective power N_e and specific fuel consumption g_e of the VOVLO DC13C460 engine as a function of speed n for the technical states of the air filter: "Clean", "Dirty"

The use of a Δp_f air filter with a "Dirty" flow resistance for testing is associated with a displacement of the N_e = f(n) characteristic toward lower engine power values. In the rotational speed range 1400–1900 rpm, the largest relative change in effective power (power drop) was observed, reaching – 10% (Fig. 8).

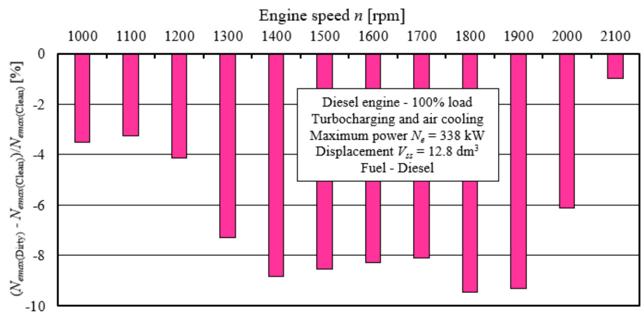

Fig. 8. Relative change in engine power due to change in air filter condition "Clean" – "Dirty"

At a rotational speed of n = 1900 rpm, the reduction in power resulting from the increase in air filter flow resistance takes on values of about 9.4%. This phenomenon occurs with the greatest intensity in the range: n = 1300–1900 rpm, which corresponds to the range of average rpm for the engine under study. This range, is the range of maximum torque for the engine under study, and is used most often when driving on expressways and highways. A reduction in maximum engine power, resulting from increases in flow resistance due to air filter contamination, is a detrimental phenomenon for motor vehicles, especially trucks. A reduction in maximum engine power can cause difficulties in climbing hills and reaching maximum speed in particular gears, especially when moving a loaded vehicle [69].

The increased resistance to air filter flow that results from the contamination of the filter element ("Dirty" condition) is important from the point of view of engine energy efficiency. As a consequence, there is an increase in specific fuel consumption – depending on the speed range and reaches a maximum of about 5% (Fig. 9).

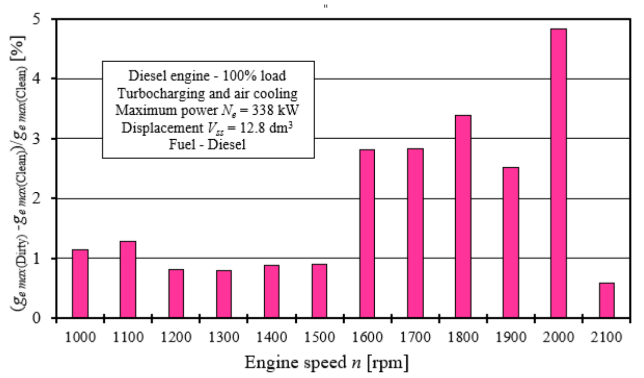

Fig. 9. Relative change in unit ge fuel consumption due to a change in the condition of the air filter "Clean"–"Dirty"

There is also a noticeable reduction in maximum useful power. The change in maximum power is the result of the Engine Control Unit (ECU), which, based on the parameters of the air in the intake system–air pressure (Fig. 6), corrects the current dose of fuel fed to the cylinder. This correction has the task of changing the thermodynamic parameters of the exhaust gas. By changing the thermodynamic parameters of the exhaust gas, an increase in charge air pressure is realized, so as to achieve the required air parameters in the intake manifold. Due to the limitations written in the control algorithm, which result from the desire to ensure the ecological properties of the engine – meeting the relevant Euro standards – it is not possible to achieve the declared maximum engine power in a situation where the flow resistance in the intake system of the engine under study increases

Changes in hourly fuel consumption G_e and exhaust gas temperature t_s as a function of the speed n of the test engine for two different flow resistance ("Clean", "Dirty") air filter states are provided in Fig. 10.

The change in air filter flow resistance from the "Clean" state to the "Dirty" state results in a decrease in hourly fuel consumption G_e, by about 7.9%. The observed phenomenon is the result of a decrease in the mass flow rate of air supplied to the engine Q_s (Fig. 5), and consequently also in the boost pressure (Fig. 6) This is a consequence of increasing flow resistance in the intake system of the vehicle under study. When creating the optimum fuel-air mixture, the fuel-air mass ratio for a given fuel type and engine is important. When too little air mass is supplied to the engine there are problems with optimal fuel-air mixing. When fuel and air are not mixed properly, fuel combustion processes in the engine's combustion chamber occur in an abnormal manner. The negative elect of the lack of complete and total combustion due to improper preparation of the fuel-air mixture is an increase in smoke and increased emissions of products of incomplete combustion – carbon monoxide and hydrocarbons. To prevent this phenomenon, the fuel dosage control algorithms implemented in the ECU reduce the maximum mass of fuel fed to the cylinder during the engine's operating process. The effect of correcting/changing the fuel dosage is to reduce the maximum engine power and hourly fuel consumption, in proportion to the reduction in air mass.

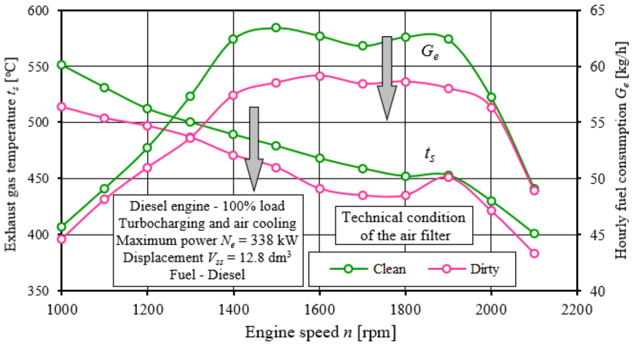

Fig. 10. The effect of technical conditions of the air filter on changes in hourly fuel consumption G_e and exhaust gas temperature t_s at the exit of the turbocharger of the engine under study as a function of engine speed n

As the engine speed increases, the exhaust gas temperature t_s, decreases slowly but steadily (almost linearly) up to a speed of n = 1800 rpm, and then a gentle increase in its value is noticeable, after which it decreases sharply again. The use of an air filter with higher flow resistance Δp_f, ("Dirty"), shifts the characteristics of $t_s = f(n)$ toward lower values of exhaust gas temperature. The results obtained for an engine operating with an air filter with a flow resistance Δp_{fD} = 2.024 kPa (Dirty), show a significant 5% reduction in exhaust gas temperature ts compared to the results obtained for engine operation with a "Clean" filter. For low and medium speeds in the range of n = 1000–1800 rpm, a reduction in exhaust gas temperature t_s of about t_s = 20–30°C was observed, depending on the measurement point. This is the result of a change/reduction in the amount of fuel and air supplied to the cylinder during engine operation.

2.5. Assessment of changes in exhaust emissions

Figure 11 shows the smoke opacity of the exhaust gas as the light radiation extinction coefficient k as a function of engine speed n for two technical states (Clean, Dirty) of the air filters. For low engine speeds n = 1000–1100 rpm, high smoke opacity was observed. The large opacity of the exhaust gas is a result of the low fill factor of the engine, which is due to the low efficiency of the turbocharger at low engine speeds. In addition, low engine speeds have problems with proper charge swirl, which promotes incomplete combustion and high emissions of incomplete combustion products including soot. When increasing the rotational speed, regardless of the condition of the air filter, it has been observed, the opacity decreases. For rotational speeds in the range of n = 1200–1700 rpm, it remains constant, and increases slightly after exceeding 1700 rpm. On the basis of the study, it was concluded that the increase in the air filter's flow resistance has no significant effect on the results of smoke opacity measurements in relation to its permissible value, which is set at 1.5 m^{-1} in the technical conditions of approval for this type of vehicle [70].

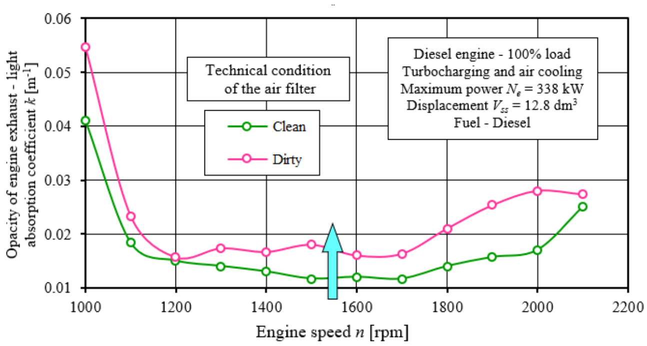

Fig. 11. Exhaust gas opacity of the VOVLO DC13C460 engine – light absorption coefficient k (absorption) as a function of engine speed n for two technical states of the air filter: „Clean" and „Dirty".

Figure 12 shows the results of measuring the concentration of carbon dioxide CO_2 in the exhaust gas of the VOVLO DC13C460 engine. The figure shows the results obtained for two different flow resistance technical states of the air filter: "Clean" and "Dirty".

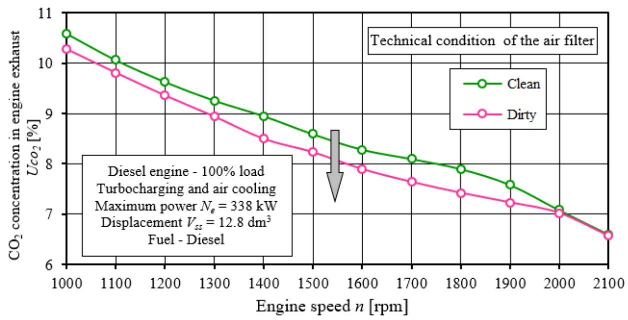

Fig. 12. CO_2 concentration in the exhaust gas of the tested engine caused by a change in the technical condition of the air filter "Clean"–"Dirty"

As the engine speed increases, the concentration of CO_2, decreases in value, until the tested engine reaches its maximum speed. The observed changes are independent of the technical condition of the air filter. Changing the engine speed in the range of n = 1100–2100 rpm results in a significant 10.28% to 6.57% reduction in CO_2 concentration in the exhaust gas, which is the result of an increase in the mass of fresh air entering the cylinders and changes in the mass of fuel delivered to the cylinders, which are due to the maximum fuel dose possible programmed in the engine controller.

The specific CO_2 emissions determined during the tests as a function of speed and the two technical states of the air filter are shown in Fig. 13. Figure 14 illustrates the relative change in specific CO_2 emissions in the engine exhaust for the "Dirty" state, compared to the emissions obtained when the engine was operated with the "Clean" air filter.

Based on the information in Fig. 12–14, it should be noted that the air filter pressure drop is quite important for CO_2 emissions. In the low speed range 1000–1200 rpm, an increase in filter pressure drop results in a decrease in CO_2 emissions. This is due to a reduction in the amount of fuel fed to the engine cylinders by the ECU engine management system, as a result of a reduction in boost pressure.

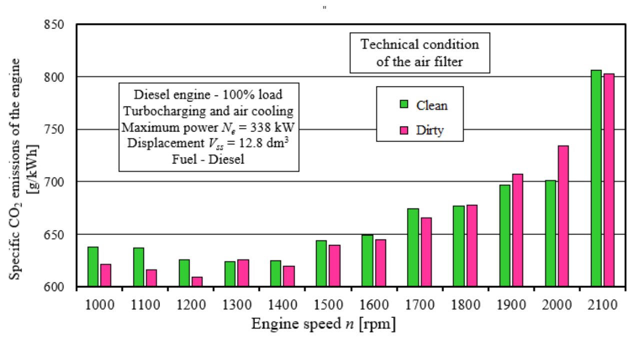

Fig. 13. Unit CO_2 emissions from the engine due to a change in the condition of the air filter "Clean"–"Dirty"

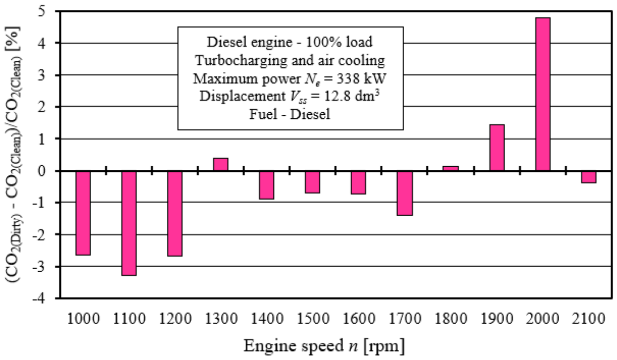

Fig. 14. Relative change in CO_2 emissions from the engine for different speeds due to a change in the condition of the air filter, relative to power with the air filter in „Clean" condition

As the engine speed increases above 1200 rpm, the effect of filter pressure drop on CO_2 emissions is reduced. This is the result of the ECU adjusting the fuel dose to the currently prevailing conditions in the engine air supply system. The relative change in CO_2 emissions does not exceed 4% (Fig. 14). For high engine speeds n = 2000–2100 rpm, a negative effect of the suspended air filter pressure drop on CO_2 emissions can be observed. This phenomenon is the result of increasing air filter pressure drop at the filter baffle of the filter as a consequence of increasing flow velocity in the filter bed. Air filter pressure drop increases as a function of speed in the second power [71]. For speeds above 1600 rpm, a controlled strategy stored in the ECU is designed to ensure adequate boost pressure by interchanging the fuel supply system's operating parameters – dose and fuel injection advance angle. This strategy is designed to provide the amount of exhaust gas necessary to ensure proper turbocharger operating conditions (increasing rpm), resulting in increased charge air pressure. This action, associated with the need to supply a greater mass of fuel to the cylinder while keeping the air mass constant, results in increased CO_2 emissions. It is an unfavorable phenomenon from the point of view of atmospheric pollution; however, in this speed range, the engine does not run very frequently.

When the engine is operated with the "Dirty" filter, there is a significant decrease in CO_2 concentration in the exhaust gas, however, there is not such a significant decrease in CO_2 emissions (Fig. 14), which is due to the simultaneous decrease in the effective power of the engine, which is a component when determining the emissions of the individual gaseous components.

This is to be explained by the fact that an increase in resistance Δp_f results in a decrease in the air flow supplied to the engine Q_s and the boost pressure. The reduction in CO_2 concentration in the exhaust gas is proportional to the change in useful power.

Based on the results in Fig. 12 and 14, it should be concluded that the increase in resistance in the intake system of a modern heavy-duty vehicle CI engine has no significant effect on the CO_2 emissions into the atmosphere.

Figure 15 shows the concentration of carbon monoxide CO in the exhaust gas as a function of rotational speed n for two different pressure drop Δp_f („Clean", „Dirty") technical states of the air filter. As the engine speed increases, the concentration of carbon monoxide CO, irrespective of the technical condition of the air filter – the value of pressure drop Δp_f, decreases its value until the engine reaches its maximum speed of n = 2100 rpm. The greatest changes (intensive decrease in CO concentration) were recorded for rotational speeds in the range of n = 1000–1200 rpm.

As the engine speed increases above 1600 rpm, the effect of pressure drop Δp_f on CO is reduced. This is a result of the engine controller adjusting the fuel delivery to the current conditions in the engine intake system – boost pressure. This problem is described in more detail when analyzing the effect of air filter pressure drop on CO_2 emissions.

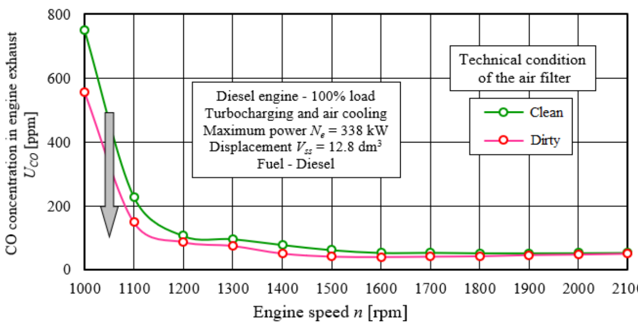

Fig. 15. CO concentration in the exhaust gas of the tested engine caused by a change in the condition of the air filter: "Clean" "Dirty"

Increasing the air filter pressure drop („Dirty") results in a decrease in CO concentration in the exhaust gas; in addition, there is a significant decrease in CO emissions (Fig. 16). This phenomenon is similar in nature to that described for CO_2 emissions.

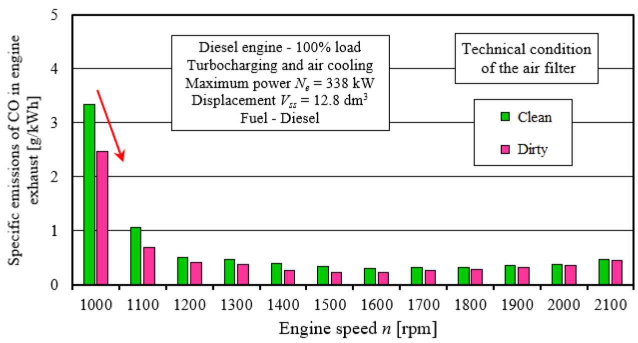

Fig. 16. Unit emission of CO in the engine exhaust due to a change in the condition of the air filter: "Clean"–"Dirty"

The specific CO emissions from the engine exhaust system for each speed caused by the technical states of the air filter p: "Clean", "Dirty" are shown in Fig. 16. The highest CO emissions occur in the 1000–1100 rpm speed range. These changes are not correlated with changes in flow resistance. On the other hand, Fig. 17 shows the determined change in specific CO emissions from the engine caused by a change in the technical state of the air from the "Clean" state to the "Dirty" state, compared to the emissions obtained when the engine was operated with a "Clean" air filter. A significant effect of flow resistance resulting from the change in the technical state of the air filter was found. The "Dirty" condition results in a 15–13% reduction in emissions for low and medium speeds, and about 5% for higher speeds. The nature of the changes is correlated with changes in the fuel flow supplied to the engine and changes in the engine's useful power.

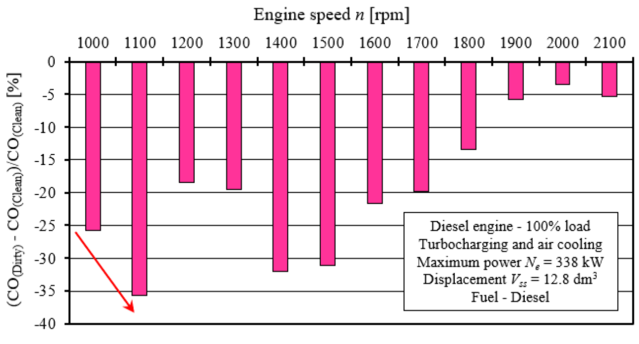

Fig. 17. Relative change in specific CO emissions in the engine exhaust for different speeds due to a change in the condition of the „Dirty" air filter, relative to power with the air filter in „Clean" condition

On the basis of the information in Fig. 15–17, it should be concluded that the condition of the air filter (distinguishable by the value of the pressure drop) is important for carbon monoxide – CO emissions. In the low to medium speed range of 1000–1700 rpm, an increase in the pressure drop of the filter element results in a reduction in CO emissions. This is a result of the ECU reducing the amount of fuel fed to the engine cylinders, as a result of a reduction in boost pressure and the desire of the implemented engine control algorithms to limit the increase in emissions of toxic exhaust components.

In addition, when analyzing the impact of the filter's technical condition (increase in pressure drop Δp_f) on CO emissions, it should also be borne in mind that the measured values in the mid- and high-speed ranges are very small – at the level of several ppm. This is the measuring range of the analyser with a high measurement uncertainty. Therefore, the nature of the changes should be interpreted qualitatively rather than strictly quantitatively.

Figure 18 shows, for two air filters differing in pressure drop („Clean", „Dirty"), the NO_x concentration as the sum of NO, NO_2 and N_2O, and Fig. 19 shows the specific NO_x emission GAS_{NOx}. The relative change in NO_x emissions from the engine for each speed caused by the air filter conditions compared to the emissions obtained when the engine was running with the „Clean" air filter is shown in Fig. 20.

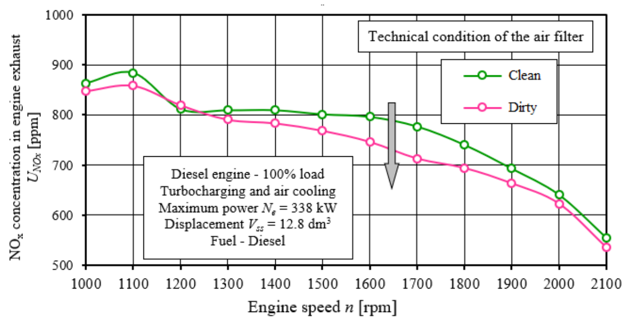

Fig. 18. NO_x concentration in the exhaust gas of the tested engine caused by the change in the technical condition of the "Clean"–"Dirty" air filter

The highest NO_x concentration of 850–890 ppm was obtained for low engine speeds. In this range, the NO_x concentration does not depend on the condition of the filter. The reason for the high NO_x concentration is the low excess air ratio, which promotes an increase in combustion temperature (Fig. 10). High temperature during the combustion process is one of the factors affecting the formation of nitrogen oxides. The small excess air ratio is the result of low boost pressure, (Fig. 6). In addition, in order for the engine to reach the required torque value in the low-speed range, a large amount of fuel is fed into the cylinder relative to the amount of air supplied.

Once the engine exceeds a speed of 1100 rpm, the boost pressure increases. The boost pressure is the result of an increase in the amount of exhaust gas supplied to the turbocharger. This results in an increase in the amount of air relative to the amount of fuel – that is, an increase in the excess air ratio. An increase in the excess air ratio is the same as an increase in the concentration of the amount of oxygen in the fuel-air mixture, resulting in a lower combustion temperature. Reducing the combustion temperature reduces the formation of NO_x and incomplete combustion products such as CO – as described earlier. The increased amount of air allows an increase in the amount of fuel fed, resulting in a sharp increase in the engine's effective power. The rate of increase in effective power is much less than the decrease in NO_x concentration in the exhaust gas. The elect of this process is higher specific emissions of NO_x (Fig. 19). Replacement of the "Clean" air filter with a filter of the "Dirty" state, entails a decrease in the concentration of NO_x in the exhaust gas, however, this is not a significant decrease in NO_x emissions from the point of view of the requirements of EURO standards.

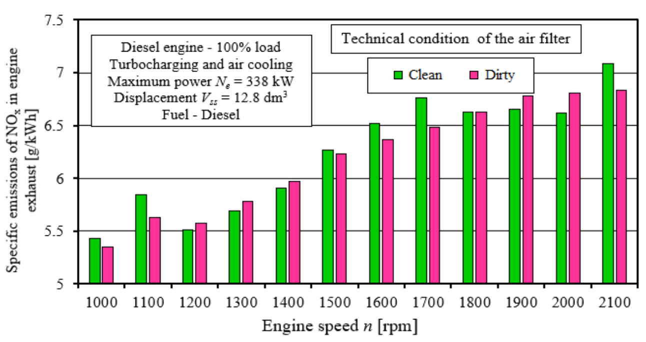

Fig. 19. Unit emission of NO_x in engine exhaust due to change in condition of air filter "Clean"–"Dirty"

Based on the data presented in Fig. 18–20, it was determined that the condition of the air filter, characterized by the flow resistance Δp_f, does not significantly affect NO_x emissions into the atmosphere. The experimentally determined changes in specific NO_x emissions range from –4 to +3%, and depend on the currently prevailing engine operating conditions and the state of the power system. The observed changes do not have a clearly identified character.

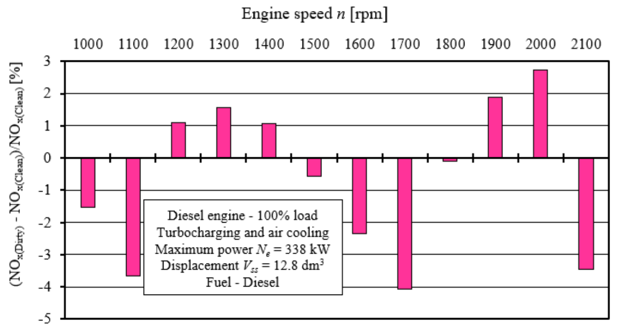

Fig. 20. Relative change in NO_x emissions in engine exhaust due to change in condition of air filter: "Clean"–"Dirty"

In the next stage of the study, the effect of the technical condition of the air filter on the concentration of HC hydrocarbons was determined. The obtained test results are shown in Fig. 21. Due to the measured values of concentrations – at the level of twenty-some ppm, the relative change in emissions was not determined. When evaluating the effect of filter condition on HC emissions, only the nature of the change in HC concentration for the air filters tested was evaluated.

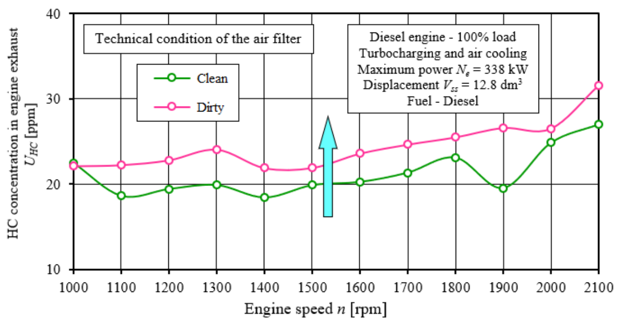

Fig. 21. HC concentration in the engine exhaust caused by a change in the condition of the air filter: "Clean"–"Dirty"

Based on the results, it should be concluded that the state of the air filter, to which a certain value of flow resistance Δp_f corresponds, has no significant effect on HC concentration. After changing the filter from the "Clean" state to the "Dirty" state, an insignificant increase in HC concentration was observed, only by a few ppm. Determined on the basis of the tests, the average HC emissions for an engine with a "Clean" air filter (Δp_{f0} = 0.58 kPa) were 0.0547 g/kWh, and for a filter in the "Dirty" state (Δp_{fD} = 2.024 kPa) were 0.0653 g/kWh, respectively. From the point of view of meeting Euro standards and the environmental characteristics of the engine under study, these values are very small, and have no significant effect on the aforementioned properties.

Figure 22 shows as a function of engine speed n the concentration of oxygen O_2 in the exhaust gas for two technical states of the same air filter.

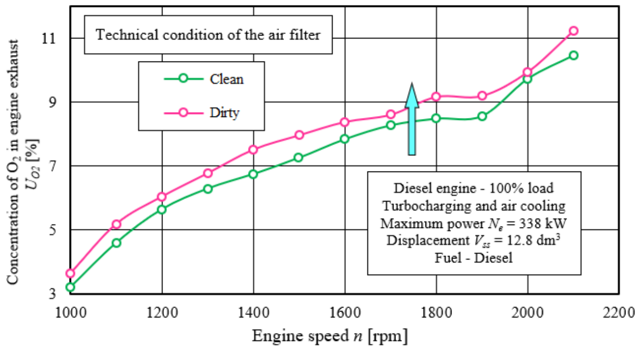

Fig. 22. O_2 concentration in the engine exhaust caused by a change in the condition of the air filter: "Clean"–"Dirty"

Increasing the pressure drop of the air filter („Dirty") results in an increase in exhaust gas oxygen emissions in the range of 7% to 15% depending on engine speed. This is explained by the fact that an increase in air filter pressure drop Δp_f results in a decrease in the air mass delivered to the engine Q_s and the boost pressure (Fig. 6). The lower mass of air supplied to the engine results in a decrease in oxygen concentration, which is a typical phenomenon for this type of process. This is the result of the engine control system reducing the maximum fuel dose delivered to the cylinder in the duty cycle to reduce the effects of the reduction in boost pressure. A reduction in boost pressure results in a reduction in the excess air ratio and leads to an increase in the concentration of particulate and toxic gaseous emissions. To counteract this phenomenon, the ECU causes a reduction in the maximum fuel delivery to the cylinders, which is reflected in a reduction in useful power (Fig. 7) and hourly fuel consumption (Fig. 10) and an increase in exhaust gas oxygen concentration (Fig. 22). The reduction in hourly fuel consumption is due to the engine control strategy, coded in the ECU, which is optimized for reducing emissions of toxic exhaust components. The reduction in fuel delivery is stronger than the reduction in useful power and boost pressure, resulting in an increase in the oxygen concentration in the exhaust gas. This is a positive phenomenon in terms of protecting the engine against an increase in toxic emissions in the event of a decrease in engine cylinder air filling due to an increase in pressure drop Δp_f of the air filter.

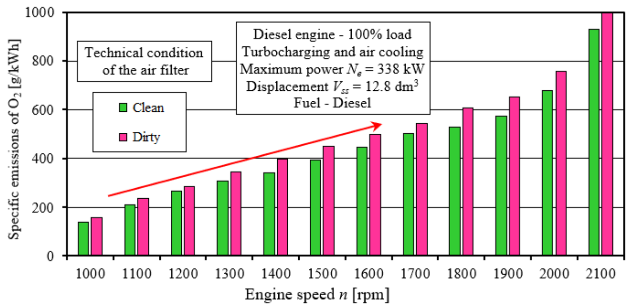

Fig. 23. Unit emission of O_2 in the engine exhaust due to a change in the condition of the air filter: "Clean"–"Dirty"

Based on the results presented in Fig. 22–24, it should be stated that the increase in pressure drop in the intake system of a modern diesel engine of a truck has a significant impact on oxygen concentration and oxygen emission in exhaust gases.

A significant increase in the pressure drop in the intake system causes a reduction in the fuel dose fed to the cylinder, which results in a reduction in power and an increase in oxygen concentration in the exhaust gases. This proves the correct selection of engine control algorithms in the case of increased pressure drop in the intake system.

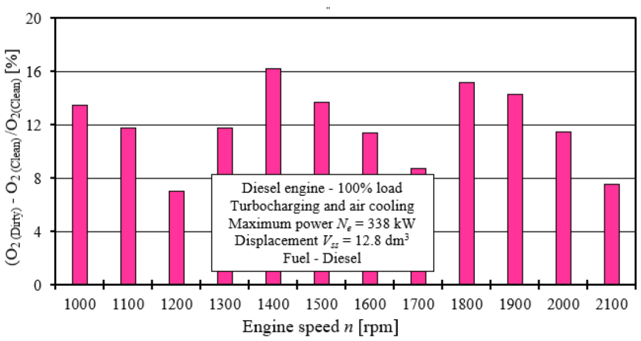

Fig. 24. Relative change in O_2 emission from the engine for particular rotational speeds n caused by a change in the technical condition of the air filter, in relation to the power with the air filter in the „Clean" technical condition

Figure 25 shows the concentration of H_2O water vapor in the exhaust as a function of engine speed n, depending on the condition of the air filter. It is observed that as the engine speed increases, the water vapor concentration decreases its value until the engine reaches its maximum speed. This phenomenon is independent of the technical condition of the air filter. For an engine speed of n = 1000 rpm, the concentration is about 10%, while for an engine speed of n = 2100 rpm, a concentration of 6% was measured. Such a significant reduction in the concentration of H_2O in the exhaust gas is the result of an increase in the mass of clean air supplied to the engine cylinders relative to the mass of fuel.

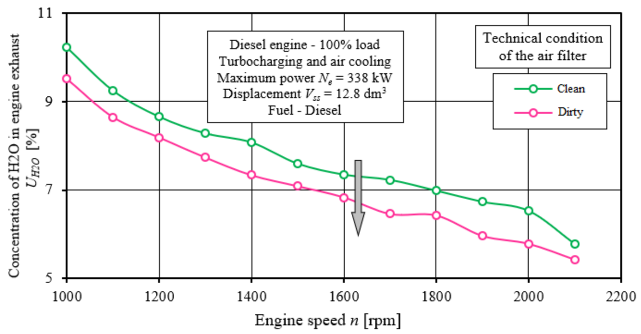

Fig. 25. H_2O concentration in the engine exhaust caused by a change in the condition of the air filter: "Clean"–"Dirty"

Changing the technical condition of the air filter from „Clean" to „Dirty" i.e. an increase in pressure drop in the range of Δp_f = 0.58–2.024 kPa, causes, at the rotational speed of n = 1900 rpm, a decrease in H_2O concentration in the exhaust gas by 11%. The increase in pressure drop in the intake system reduces the amount of fuel supplied to the cylinder, which results in a decrease in CO_2 concentration and a decrease in water vapor concentration.

Increasing (Fig. 26) the air filter flow resistance from the "Clean" state to the "Dirty" state results in a significant reduction in evaporative emissions in the range of 3 to 7%. This phenomenon is associated with an increase in the air flow supplied to the engine Q_s (Fig. 5) and simultaneous changes in air pressure in the supercharging system (Fig. 6). A smaller mass flow of air that is directed into the engine cylinders entails a decrease in the mass of fuel supplied, which produces water vapor during sapping.

Increasing air pressure drop results in a significant reduction in H_2O emissions (Fig. 27). Changing the technical condition of the air filter from „Clean" and „Dirty" causes a decrease in the concentration of H_2O in the exhaust gases by a maximum of 11%.

Changing the pressure drop of the air filter causes a significant emission of water vapor in the range of 3 to 7%. This phenomenon is the result of energy processes taking place in the engine, resulting from changes in the excess air ratio, supercharged pressure, effective power and hourly fuel consumption.

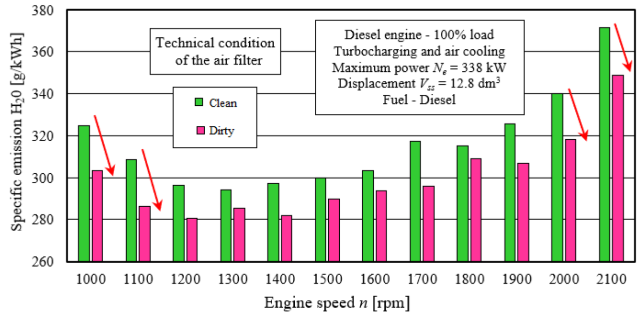

Fig. 26. Unit emission of H_2O in engine exhaust due to change in condition of air filter: "Clean"–"Dirty"

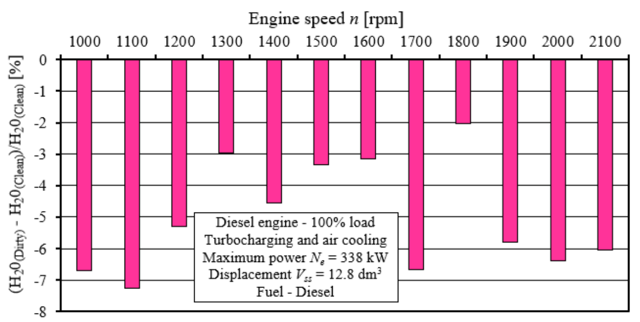

Fig. 27. Relative change in H_2O emissions from the engine for each speed n caused by a change in the condition of the „Dirty" air filter, relative to power with the air filter in „Clean" condition

Figure 28 shows the relative changes in power, useful power, specific fuel consumption and emissions of individual exhaust components for two characteristic speeds of 1400 rpm and 1900 rpm. For the tractor-trailer from which the engine under study was derived, 1400 rpm is the speed at which the engine operates most often when driving in highway conditions – a speed of 86–88 km/h.

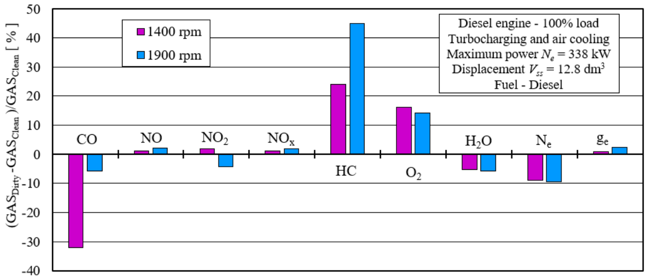

Fig. 28. Relative change in power N_e and specific fuel consumption g_e and emissions from the VOVLO DC13C460 engine for two characteristic speeds n = 1400 rpm and n = 1900 rpm caused by a change in the technical condition of the "Dirty" air filter, relative to power N_e and g_e emissions with the air filter in the "Clean" condition

At this speed, the engine's operation is most efficient – the lowest fuel consumption. The speed of 1900 rpm is the speed of maximum power. This speed is used when accelerating the vehicle with a load, for example: when driving with a semi-trailer, when the total weight of the vehicle approaches the maximum permissible value, which for this type of vehicle is 36 to 40 tons, depending on the version of the transport trailer.

The reduction in carbon monoxide emissions, in the mid-speed range, is the result of a control strategy stored in the ECU, which reduces the amount of fuel fed to the engine's cylinders, because of a reduction in boost pressure and an effort to limit the increase in emissions of toxic exhaust components.

The increase in HC hydrocarbon emissions in the mid- and high-speed ranges is associated with very low HC concentrations (several ppm), which, with the high measurement uncertainty of the analyzer in the range of up to 25 ppm, results in large determined emission changes.

3. Conclusions

The literature available from the recent period lacks the results of studies of modern truck internal combustion engines in the area of the effect of flow resistance in the intake system on changes in emissions of toxic components of exhaust gases and greenhouse gases such as water vapor. The bench tests presented in this paper on the changes in filter flow resistance on the operating conditions of a modern compression-ignition engine used to drive a tractor-trailer, confirm only to some extent, the results of research in the subject literature. This is due to the fact that over the past several years there has been a fundamental change in engine control systems, including air and fuel supply systems. In modern engines, power systems and control of effective engine parameters are based on multi-parameter algorithms, optimized in the direction of minimizing particulate emissions of toxic exhaust components. Providing the required useful power under the given conditions is a subordinate function.

Based on the engine tests obtained, it can be concluded that increasing air filter flow resistance causes the following effects on engine performance and exhaust emissions:

1. An increase in airflow resistance in the intake system of the VOLVO engine by 2 kPa compared to the value obtained for the new "Clean" filter results in a decrease in effective power by 9.31%, which, with respect to a 1 kPa increase in flow resistance, amounts to 4.66% and is a magnitude 10 times greater than that of engines with a mechanically controlled fuel supply system. The observed changes in horsepower are correlated with changes in mass airflow delivered to the engine (3.39%) and boost pressure (4.28%).
2. There are no significant changes in CO_2 concentration and emissions. For low speeds of 1000–1200 rpm, increasing the filter flow resistance results in a slight reduction in CO_2 emissions. When increasing the rotational speed, a reduction in the effect of filter flow resistance on CO_2 emissions was observed, and the relative changes in CO_2 emissions do not exceed 4%.
3. Influences on CO concentrations and emissions. With the increase of engine speed above 1600 rpm, the effect of the effect of flow resistance Δp_f on CO emissions is reduced. When the engine is operated with the air filter in the "Dirty" state, the changes in CO emissions are 10–13% for low and medium speeds and about 5% for higher speeds. The nature of the changes is correlated with changes in hourly fuel consumption and useful engine power.
4. No significant impact on NO_x emissions was observed. The observed changes in NO_x emissions oscillate between –4 and +3%, depending on the current engine operating conditions and the state of the air supply system. The observed changes are not clearly identified.
5. There is no significant effect on HC concentration. The observed changes oscillate around the detection threshold of the exhaust gas analyzer used.
6. Has a significant effect on oxygen emissions. Increasing the flow resistance of the air filter increases the concentration of oxygen in the exhaust gas and increases its emissions by 7% to 15% depending on the engine speed.
7. Has a significant effect on the concentration and emission of water vapor. An increase in resistance in the air intake system entails a significant reduction in H_2O emissions. This phenomenon is positively correlated with an increase in flow resistance. A change in the technical condition of the air filter from "Clean" to "Dirty", causes, a decrease in H_2O concentration in the exhaust gas by a maximum of 11% and a decrease in water vapor emissions in the range of 3 to 7%.

The next stage of the research should be to evaluate the effect of changes in the flow resistance of the air supply system on the traction characteristics of a truck tractor with the tested engine equipped with this type of intake system.

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Nomenclature

CI compression ignition
ECU Electronic Control Unit
SI spark ignition
T-PR-C piston-piston ring-cylinder

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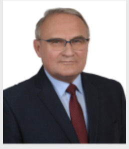

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