ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.2452

PERFORMANCE CHARACTERISTICS OF PANEL FILTERS FOR INTERNAL COMBUSTION ENGINE INLET AIR WORKING IN A TWO-STAGE CONFIGURATION

Tadeusz Dziubak

Military University of Technology, Faculty of Mechanical Engineering
Institute of Motor Vehicles and Transportation
Gen. Witolda Urbanowicza Street 2, 00-908 Warsaw, Poland
tel.:+48 261 837121
e-mail: tadeusz.dziubak@wat.edu.pl

Abstract

Air filtration conditions in a single-stage and a two-stage filtration system (multicyclone-porous panel filter) are presented. Allowable flow resistance Δp_{fdop} values reducing the air filter service life are specified. The benefits of using a multicyclone as a first stage of air filtration, including improved mobility and extended service life, are discussed. Criteria for selecting the filter media for the automobile air intake system using an absorption coefficient of dust k_m determined at a specific allowable flow resistance Δp_{fdop} are specified. New methods and conditions to determine the absorption coefficient of dust k_m for article filter and non-woven fabric filter in a single-stage and a two-stage filtration system are developed and presented. The separation efficiency and separation performance as well as the flow resistance characteristics of the filter set including a single cyclone and a filter element with a specially selected filter medium surface area are tested. Absorption coefficients of dust k_m for the tested paper filter and non-woven fabric filter were determined for an allowable flow resistance. The effects of dust particle size distribution in the air downstream of the cyclone on reducing the absorption coefficient of dust of the paper filter and non-woven fabric filter in a two-stage filtration system are shown.

Keywords: *two-stage air filter, filter medium, separation efficiency, flow resistance, absorption coefficient of dust*

1. Introduction

An air supply system of an internal combustion engine (air intake system) supplies and filters the outside air to the engine cylinders to reduce wear of system components in a quantity and with the parameters to ensure suitable conditions for the combustion process in the engine cylinders. The air intake system of a modern internal combustion engine includes the following components: air filter with air intake, flowmeter, turbo-compressor (as standard in Diesel engines), radiator, suction manifold, and cylinder head inlet tract with valves.

Inlet air filtration systems in modern passenger car engines uses air filters with a porous panel filter usually are made of paper or less often a non-woven fabric. Trucks, heavy vehicles, military vehicles (mostly tanks, infantry combat vehicles, armoured personnel carriers) used at high dust concentration conditions are usually fitted with a multi-stage, usually a two-stage filter system. The first filtration stage is an inertial filter (multicyclone-tens of cyclones in parallel or monocyclone with vortex-inducing guide vanes), and the second filtration stage is a porous paper panel filter (Fig. 1).

The truck engine's air filter outlet is fitted with an allowable flow resistance sensor. The allowable flow resistance Δp_{fdop} of the air filter should prevent a reduction in engine power by over 3% [6]. Δp_{fdop} is usually between 5-8 kPa. An increase in flow resistance Δp_f at the air filter by 1 kPa will result in an average reduction in engine power by ZI ΔN_e = 1-1.5% and an increase in unit fuel consumption by Δg_e = 0.7%. For Diesel engines, the values are ΔN_e = 0.4-0.6% and

Δg_e = 0.3-0.5%, respectively [4]. The moment Δp_{fdop} is reached is indicated by the sensor and shows that the filter requires maintenance.

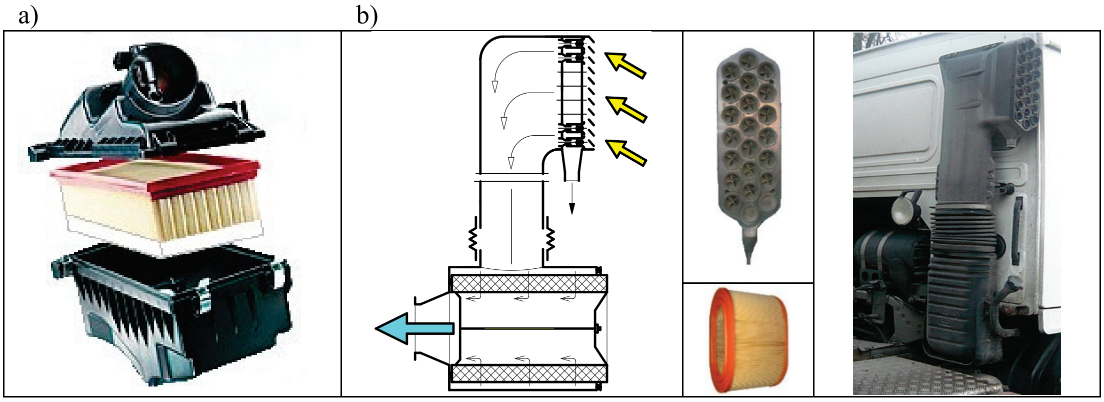

Fig. 1. Air filtration system: a) single-stage (porous panel filter) of a passenger car b) two-stage (multicyclone-porous panel filter) of a truck

Inertial filters can separate a large volume of dust from a large stream of air (separation efficiency 86% to 97%) at low separation performance. Depending on the aerosol flow conditions in the cyclones, the size of the dust particles in the outlet air downstream of the cyclone is below 15-35 μm (based on the data available in the literature [13, 16, 18] and tests of a single cyclone carried out by the author [5, 7-9, 11]).

Only a small fraction of the dust mass in the inlet air is transferred to the second filtration stage (paper filter element). Since the porous panel filter has a limited absorbing capacity, the time in which the air filtration system reaches the allowable flow resistance Δp_{fdop} (5-8 kPa) is significantly longer compared to the panel filter itself, under the same dust concentration conditions, thus increasing the vehicle mobility (Fig. 2).

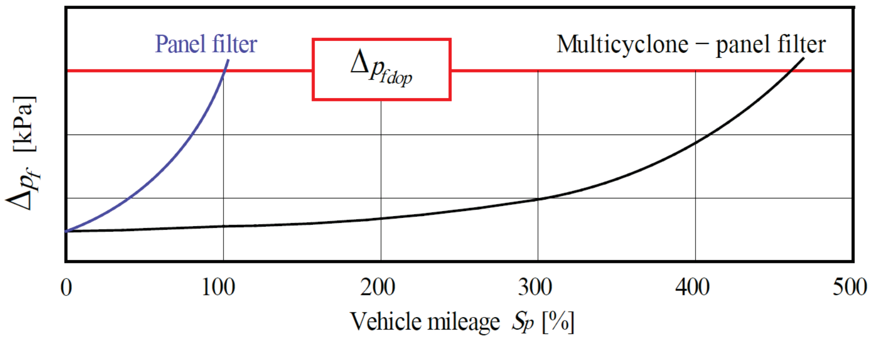

Fig. 2. Changes in flow resistance of a single-stage air filter (porous panel filter) and two-stage filters in a "multicyclone-porous panel filter" configuration

The study discusses problems when selecting a suitable air filter for the engine and presents an original method to determine the absorption coefficient of dust k_m of the filter media used as the first and the second filtration stage-downstream of the inertial filter.

2. Selecting engine air filter

The concept of using a two-stage filter consists in an initial separation of large dust particles in an inertial filter while the small dust particles (d_z < 15-30 μm) are left in the air stream and further separated (above d_z = 2-5 μm) in the panel air filter (Fig. 3).

In the two-stage filter used in a "multicyclone-porous panel filter" configuration, the filter medium absorbs the dust downstream of the inertial filter (multicyclone) with a particle size distribution different from the dust at the filter inlet.

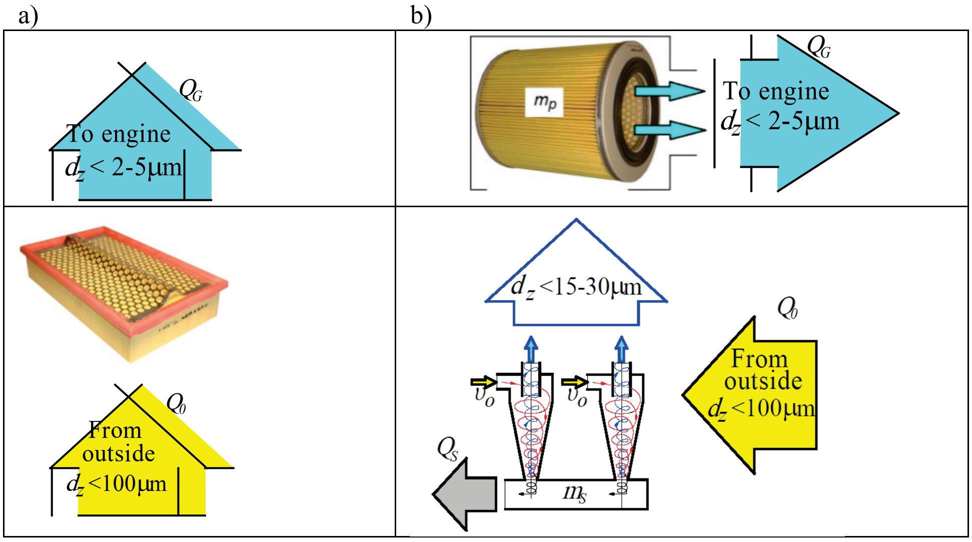

Fig. 3. Air filtration process: a) single-stage filter (porous panel filter) b) two-stage filter (multicyclone-porous panel filter) of a truck [6]

The filter element installed in parallel downstream of the multicyclone absorbs the dust particles smaller than (15-35) μm. The single-stage filter absorbs significantly larger dust particles up to 100 μm. Thus, the filtration process in the first and the second case may be different. As a result, a reduction in the absorbing capacity of the panel filter and a sudden increase in the flow resistance (faster compared to the standard particle size distribution) can be observed, thus reducing the service life of the filter. A known absorption coefficient of dust k_m of the filter medium used as a second filtration stage (downstream of the multicyclone) is important when designing the air filter to determine the mileage of the vehicle until the allowable air flow resistance Δp_{fdop} is reached.

In practice, selecting the engine air filter consists in determining the active surface area of the filter medium A_c (most often paper or non-woven fabric) to meet the condition of the allowable air flow rate via a filtration bed – filtration rate υ_{Fdop} at nominal engine's air demand. When designing the air filters (selecting a suitable filter paper) for Diesel engines used in trucks, the allowable filtration rate should not exceed υ_{Fdop} = 0.03-0.06 m/s [1, 3, 12, 15, 23, 25, 26]. The active filtration surface area is determined using the following relationship:

$$A_c = \frac{Q_{Ns}}{3600 \cdot \upsilon_{Fdop}} \, [\mathrm{m}^2]. \tag{1}$$

Based on the tests, the coefficient is not sufficient to ensure a required air filter service life, which is limited by an allowable flow resistance Δp_{fdop}, used as a criterion for the end of its service life. Filter service life until Δp_{fdop} is reached does not only depend on the air filtration process parameters of the porous panel filter, but also on the absorbing capacity due to its structure and the size of retained dust particles.

It is also important, if the surface area A_c selected based on the allowable filtration rate will ensure a required service life of the filter corresponding to the vehicle mileage from maintenance (replacement of the filter element) at the allowable flow resistance determined based on the reduction in engine power. The data can be obtained during the performance tests of complete air filters directly on the vehicle or during the laboratory tests. The tests are expensive, labour consuming and complex. It is much easier to determine the service life τ_p of the two-stage air filter based on a theoretical relationship [4, 20].

$$\tau_p = \frac{A_c \cdot k_m \cdot k_c}{Q_{Ns} \cdot s \cdot (1-\varphi_m) \cdot \varphi_p}, \tag{2}$$

where:

A_c – active surface area of the filter paper at the second filtration stage,

k_m – absorption coefficient of dust of the filter paper at allowable flow resistance Δp_{fdop},

k_c – coefficient allowing for the difference between test and actual parameters of dust particles,

Q_{Ns} – engine's nominal air demand,

s – average dust concentration of inlet air,

φ_m – separation efficiency of the first stage of filtration (multicyclone),

φ_p – filter paper separation efficiency.

The problem with the correct application of the equation is the need to obtain extensive experimental data for a specific paper filter: absorbing capacity k_m, separation efficiency φ_p, and coefficient k_c in specific operating conditions, including: dust concentration, its chemical composition and particle-size distribution, airflow rate and dust type. The manufacturers of filter papers specify the following parameters defining the filter structure: thickness, pore size, basis weight, mechanical strength, flow resistance, permeability, and density.

To determine the required vehicle mileage (air filter service life) in specific operating conditions, the dust absorption capacity of the filter medium must be known. This property is characterized by an absorption coefficient of dust k_m for the filter paper (assuming a uniform dust distribution on the entire active surface area of the filter paper of the tested filter element) defined by the following relationship [4, 6, 10, 11]:

$$k_m = \frac{m_{cw}}{A_c} \text{ [g/m}^2\text{]}, \tag{3}$$

where:

m_{cw} – total mass of dust retained by the filter element from the point of reaching the allowable flow resistance Δp_{fdop}.

For standard cellulose-based filter media and standard dusts, with a particle size below 100 μm, the coefficient is k_m = 240 g/m^2 [3]. In a two-stage filter used in a "multicyclone-porous panel filter" configuration, the filter element installed in parallel downstream of the multicyclone absorbs the dust particles characterized by a different particle size distribution than the particles at the filter inlet. It significantly affects the filtration process in the porous panel filter, and thus its absorbing capacity. To design the filter element of a two-stage filter, the properties of the filter material corresponding to the operating conditions of the second-stage air filter must be known.

A filtration process of small dust particles at the panel filter has not been thoroughly researched and described in the available literature.

Study [6] shows a novel and simple method to determine the characteristics of a two-stage air filter by separating a filter segment in form of a single cyclone and a tested filter element installed in series as a representative segment of the actual filter element. Two-section segment separated from the filter is referred to as a "filter set". If the operating conditions of the tested filter element and the cyclone, occurring during the operation of a complete air filter with actual dimensions are maintained during the tests of the filter element, the results can be treated as representative for the actual filter element.

Filter panels in the inlet air filter of the combustion engine are made of filter paper with various structural parameters and properties: basis weight, thickness, air permeability, pore size and tear strength. Non-woven fabric filters are characterized by twice the basis weight are several times thicker and feature significantly lower rigidity compared to the filter paper. Those are used in the production of filter panels for passenger cars, in particular manufactured in Asia (Japan, South Korea).

The studies of non-woven fabric filters mainly show the effects of selected non-woven fabric parameter (thickness, fibre packing density) or aerosol parameter (particle size, separation rate) on the achieved separation efficiency [2, 18]. Some sources specify the absorption coefficient of dust for non-woven fabric ones, however, the values are discrepant. For example, in the study [24], the absorption coefficient of dust for a non-calendered non-woven fabric with a thickness of 3.2 mm, determined at a flow resistance of 0.3 kPa is k_m = (54.5-89.3) g/m^2, and for the same calendered non-woven fabric is k_m = (85.5-112.3) g/m^2. In [3], the absorption coefficient of dust of a layered non-woven filter fabric is k_m = (900-1100) g/m^2, however no flow resistance was specified. As per [28], the absorption coefficients of dust for non-woven filter fabrics exceed (400-480) g/m^2; however, no information was given regarding the test conditions and the test dust used.

3. Purpose, scope and subject of tests

The purpose of the study was to evaluate the effects of the particle size distribution of the dust (standard and modified by the cyclone) on the absorption coefficient of dust k_m of the filter paper and non-woven fabric filter used as the second filtration stage (downstream of the cyclone) and without cyclone. The subject of the study was a filter paper 1703 VH206 and a non-woven fabric filter AC-301 manufactured by Korea Filtration Technologies Co., with parameters specified in Tab. 1. Both filter media feature different structural parameters.

Tab. 1. Filter paper 1703 VH 206 [27] and non-woven fabric filter AC-301 [28] parameters

Parameter	Unit	1703 VH 206	AC-301
Basis weight	g/m^2	137	210 ± 10%
Thickness	mm	0.56	2.34
Air permeability	dm^3/m^2/s	270 at 200 Pa, A=20 cm^2	80-110 at 120 Pa

Two cylindrical test filter elements were made based on the AP 019 filter element by WIX Filtron (Fig. 4b and Fig. 4c). Paper surface area A_p and non-woven fabric surface area A_w were selected to ensure that the condition of an allowable (maximum) filtration rate $\upsilon_{Fdop} \leq 0.06$ m/s was met at maximum air stream flowing from a single cyclone Q_{Gmax}, and resulting from the engine's air demand Q_{Ns} at a speed corresponding to maximum engine power n_N. A single cyclone (Fig. 4) from the multicyclone of the truck's air filter was used as the first filtration stage of the "filter set".

The scope of test involved determining the following characteristics at a constant filtration rate $\upsilon_F = 0.06$ m/s, as a function of the absorption coefficient of dust k_m:

– separation efficiency $\varphi = f(k_m)$,

– separation performance (maximum dust particle size) $d_{zmax} = f(k_m)$,
– flow resistance $\Delta p = f(k_m)$.

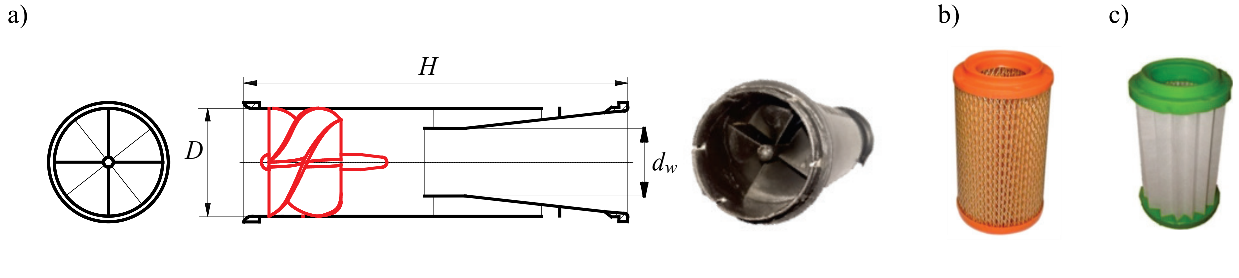

Fig. 4. "Filter set" components: a) cyclone (D = 35 mm, d_w = 23.4 mm, H = 124 mm) b) paper filter element 1703 VH206; c) non-woven fabric filter AC-301

Two filter elements with different properties used as part of the "filter set" as the second filtration stage (downstream of the cyclone) and without cyclone. The tests were carried out until the filter element achieved the actual value of the allowable flow resistance Δp_{dop} = 5 kPa.

4. Test methods and conditions

To determine the absorption coefficient of dust k_m, the mass of the dust m_{cw} retained at 1 m^2 of the filter medium (paper, non-woven fabric) until the allowable flow resistance Δp_{fdop} is reached must be known. The method specified in [6] allows to determine the coefficient k_m and performance parameters of the section of a filter paper (tested filter element) used as a second filtration stage downstream of the inertial filter-cyclone.

The tests were carried out at a test stand (Fig. 5) with the "filter set" including a single cyclone, a part of the air filter multicyclone and a cylindrical filter element installed in series, including the tested filter paper or non-woven fabric filter.

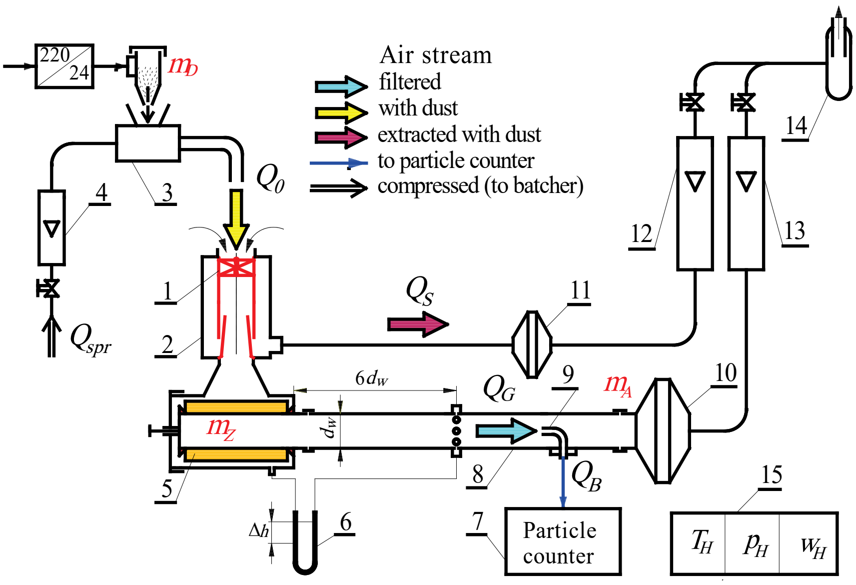

Fig. 5. Functional diagram of the test stand for filter papers in a "cyclone – panel filter" configuration: 1 – cyclone 2 – dust collector, 3 – dust dispenser, 4 – compressed air measurement rotameter, 5 – tested filter element, 6 – liquid manometer, 7 – particle counter, 8 – measuring line, 9 – dust probe, 10 – main line absolute filter, 11 – suction line absolute filter, 12 – suction stream rotameter, 13 – main stream rotameter, 14 – suction fan, 15 – hytherograph

The test stand includes a particle counter to determine the number and size of dust particles in the air stream downstream of the tested filter element, ranging from 0.7-100 µm.

Separation parameters of tested filter media were determined using a gravimetric method (determining the mass of retained and supplied dust) in subsequent j measuring cycles at specific intervals, using PTC-D test dust, an equivalent of AC Fine test dust, with chemical composition and particle size distribution specified in [22].

During the tests of the "filter set", dust concentration in the cyclone inlet air was s = 1 g/m^3, and during the tests of the panel filter (filter element), the concentration was s = 0.5 g/m^3. The tests were carried out in j measuring cycles (uniform dust batching time) τ_p = 3 min in the initial period and τ_p = 9-12 min in the main period of filter element operation. After each measuring cycle j, the parameters needed to calculate: separation efficiency, separation performance, flow resistance and absorption coefficient of dust for the filter element were determined.

Flow resistance Δp was determined as a decrease in static pressure at the outlet line at a distance of $6d_w$ from the outlet of the filter element based on the Δh_j [mm H_2O] readouts of the U-tube manometer, in accordance with the following relationship:

$$\Delta p_j = \frac{\Delta h_j}{1000} \cdot 9.80665 \text{ [kPa]}. \tag{4}$$

Separation efficiency of the filter element without cyclone was determined using the following relationship:

$$\varphi = \frac{m_{Zj}}{m_{Dj}} \cdot 100 \text{ [\%]}, \tag{5}$$

where:

m_{Zj} – mass of dust retained in time τ_{pom} at the filter element in the subsequent measuring cycle j,

m_{Dj} – mass of dust uniformly distributed at the filter element with the inlet air stream in the subsequent measuring cycle j.

Separation efficiency of the filter element used as a second filtration stage (downstream of the cyclone) was determined using the following relationship:

$$\varphi_j = \frac{m_{Zj}}{m_{Zj} + m_{Aj}} \cdot 100 \text{ [\%]}, \tag{6}$$

where:

m_{Aj} – mass of dust retained by the absolute rated filter in time τ_{pom} of the subsequent measuring cycle j.

Separation performance of the cyclone was determined based on the measurements of the number and size of dust particles, as the largest dust particle $d_z = d_{zmax}$ in a specific test cycle in the air stream downstream of the filter element.

Absorption coefficient of dust k_{mj} was determined from the following relationship:

$$k_{mj} = \frac{\sum m_{Zj}}{A_c} \text{ [g/m}^2\text{]}. \tag{7}$$

5. Test result analysis

Fig. 6 and 7 show the test results for the following properties: separation efficiency and separation performance and flow resistance of the filter elements as a function of the absorption coefficient of dust k_m used in the "filter set" as the second filtration stage (downstream of the cyclone) and without cyclone.

The service life of the filter element can be divided into two periods due to the achieved separation efficiency. The first period (I_p, I_{Zp} – Fig. 6b, I_w, I_{Zw} – Fig. 7b) is characterized by low separation efficiency, systematically and rapidly increasing with the increase in the mass of dust retained by the paper filter (non-woven fabric), and thus with the increase in the absorption coefficient of dust k_m.

The initial filtration period lasts from the beginning of the separation process until the maximum separation efficiency of the paper (non-woven fabric) is reached. During the tests, the changeover between the filtration periods was observed at the separation efficiency of $\varphi = 99.5\%$ [2, 3]. The main filtration period (II_p, II_{Zp}) is characterized by the stabilisation of separation efficiency at $\varphi = 99.5$-99.98% and constant increase in flow resistance (Fig. 6).

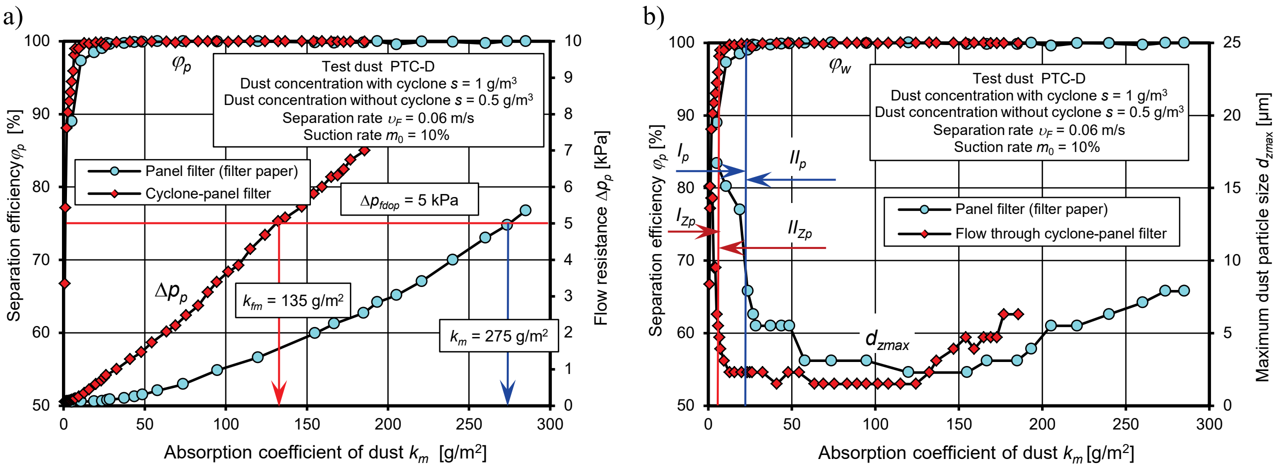

Fig. 6. The properties of the paper filter used in the filtration system as a second filtration stage (downstream of the cyclone) and without cyclone): a) separation efficiency $\varphi_p = f(k_m)$ and flow resistance $\Delta p_p = f(k_m)$; b) separation efficiency $\varphi_p = f(k_m)$ and separation performance $d_{zmax} = f(k_m)$ as a function of the absorption coefficient of dust k_m

After the first measuring cycle, the separation efficiency of the paper filter element without the cyclone was $\varphi_{p1} = 89\%$, and with the cyclone was $\varphi_{p2} = 66\%$ (Fig. 6). Separation efficiency of the non-woven fabric filter was: $\varphi_{w1} = 93\%$ and $\varphi_{p2} = 78\%$, respectively (Fig. 7).

The initial filtration period lasts from the beginning of the separation process until the maximum separation efficiency of the paper (non-woven fabric) is reached. During the tests, the changeover between the filtration periods was observed at the separation efficiency of $\varphi = 99.5\%$ [2, 3]. The main filtration period (II_p, II_{Zp}) is characterized by the stabilisation of separation efficiency at $\varphi = 99.5$-99.98% and constant increase in flow resistance (Fig. 6).

After the first measuring cycle, the separation efficiency of the paper filter element without the cyclone was $\varphi_{p1} = 89\%$, and with the cyclone was $\varphi_{p2} = 66\%$ (Fig. 6). Separation efficiency of the non-woven fabric filter was: $\varphi_{w1} = 93\%$ and $\varphi_{p2} = 78\%$, respectively (Fig. 7).

In the initial filtration period, the maximum dimensions of dust particles (flowing through the filter element) in the air downstream of the paper filter element (without cyclone) were $d_{zmax} = 16.7$ µm, whereas the maximum dimensions of dust particles downstream of the non-woven fabric filter were $d_{zmax} = 22$ µm. With the increase in the absorption coefficient of dust k_m the dust particle diameters d_{zmax} decrease, and for the paper element without cyclone the values are stabilized at $d_{zmax} = 5.5$ µm after reaching $k_m = 28.5$ g/m^2, and with cyclone – the average values stabilize at a lower level ($d_{zmax} = 2.3$ µm) and significantly earlier at $k_m = 12.7$ g/m^2 (Fig. 6b).

A similar effect can be observed for the non-woven fabric filter element; however, the dust particle diameter d_{zmax} is stabilized at a slightly higher level and at higher values of the absorption coefficient of dust k_m compared to the paper filter (Fig. 7a). The initial filtration period of the non-woven fabric filter (I_w, I_{zw}) takes longer. After the non-woven fabric filter element without cyclone reaches k_m = 72.2 g/m^2, the air contains dust particles with a diameter of d_{zmax} = 6.2 µm, whereas the diameters are stabilized at approx. d_{zmax} = 3.8 µm for the filter element with cyclone. When the dust particles with maximum dimension of d_{zmax} are stabilized, the main (stable) operation period of the filter element commences, until the allowable flow resistance Δp_{dop} = 5 kPa is reached.

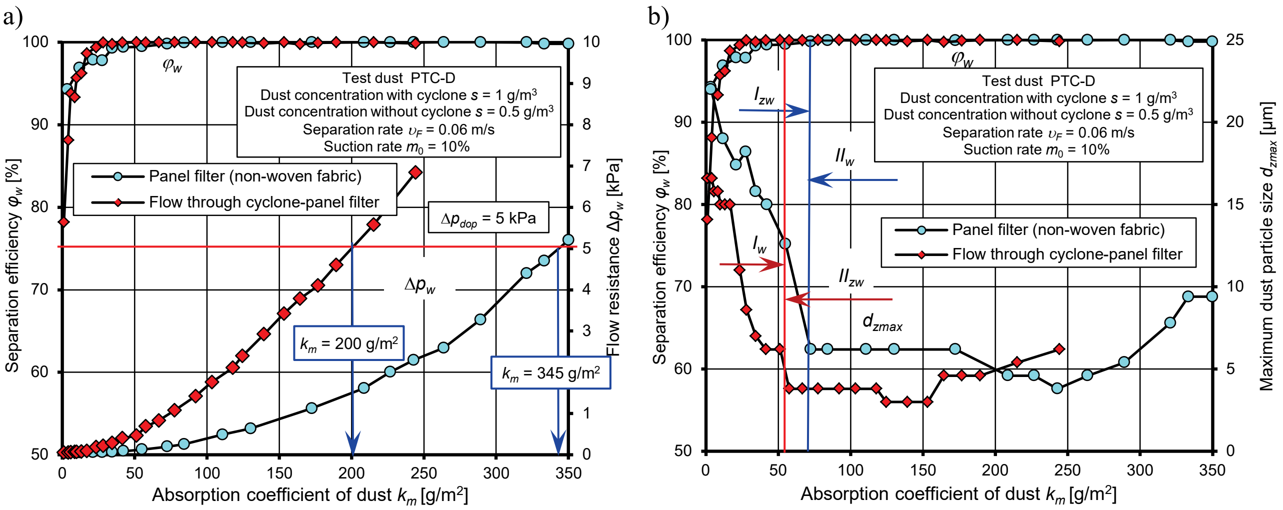

Fig. 7. Properties of the non-woven fabric filter used in the "filter set" as the second filtration stage (downstream of the cyclone) and without cyclone): a) separation efficiency $\varphi_w = f(k_m)$ and flow resistance $\Delta p_w = f(k_m)$; b) separation efficiency $\varphi_w = f(k_m)$ and separation performance $d_{zmax} = f(k_m)$ as a function of the coefficient of dust absorption k_m

The course of the separation performance and flow resistance curves can be explained by the fact that the initial dust particles retained by the panel filter are the source of secondary structural elements. The dust particles can be retained not only by the fibres, but also on the previously retained particles. Extensive agglomerates (Fig. 8), filling all the empty spaces between the fibres are formed, which means that smaller particles are retained, and the aerosol flow rate is reduced, resulting in an increase in flow resistance with an increase in mass of dust retained by the filter element.

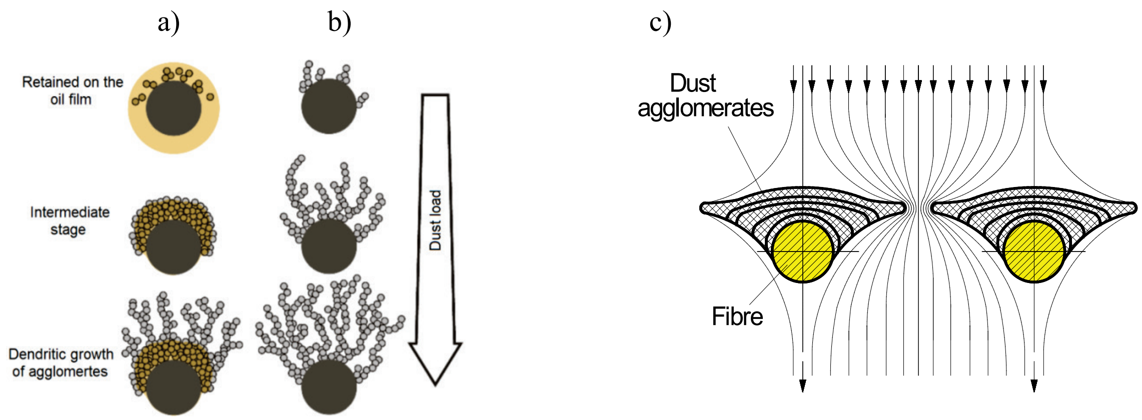

Fig. 8. Agglomerate forming diagram: a) phases of dust particle retaining on the non-woven fabric filter oil wetted b) dry [21], c) aerosol flow between the fibres covered with dust agglomerates

The exact explanation of this effect is not simple due to the fact that the aerosol filtration process is stochastic in nature, difficult to quantify and qualify. The particle retention process in the porous panel filter depends on many forces and phenomena. The particles and components of the porous medium have irregular shape and irregular surface microstructure. The dust particles settle uniformly on the surface of the fibres. The porosity of the panel filter is reduced, and the retained particles can be removed by the flowing liquid stream.

With the increase in the absorption coefficient of dust k_m the flow resistance Δp_f of the tested filter elements increases gradually. For the filter paper without the cyclone, Δp_p = 5 kPa was reached at the absorption coefficient of dust k_m = 275 g/m^2, and with the cyclone, the absorption coefficient of dust was 50% lower at k_m = 135 g/m^2 (Fig. 6). Flow resistance Δp_p, a criterion for replacement of the filter element, increases more rapidly if the panel filter is subject to dust, whose particle size distribution was changed by the cyclone due to the different effects and filtration mechanisms.

For the non-woven fabric filter element without the cyclone, Δp_p = 5 kPa was reached at the absorption coefficient of dust k_m = 345 g/m^2, and with the cyclone, the absorption coefficient of dust was lower at k_m = 200 g/m^2 (Fig. 7).

Small dust particles penetrate the filter paper structure more easily and fill it to a larger degree compared to the particles with higher diameter. Empty spaces between the retained small dust particles are significantly smaller than for the large dust particles, increasing the aerosol flow rate and the flow resistance.

The curves show that using the inertial filters as a first filtration stage results in retaining large (over 25-35 μm) and letting through small particles, reducing the dust absorbing capacity of the filter medium used as the second filtration stage.

Fig. 9 shows the predicted mileage of a vehicle fitted with a single-stage filtration system (filter paper, non-woven fabric) and two-stage filtration system (cyclone-panel filter). The calculations were carried out using the calculated absorption coefficients of dusts k_m. The vehicle fitted with a single-stage filtration system reaches S_{pI} = 18000 km and S_{pI} = 22500 km for paper and non-woven fabric filter element, respectively.

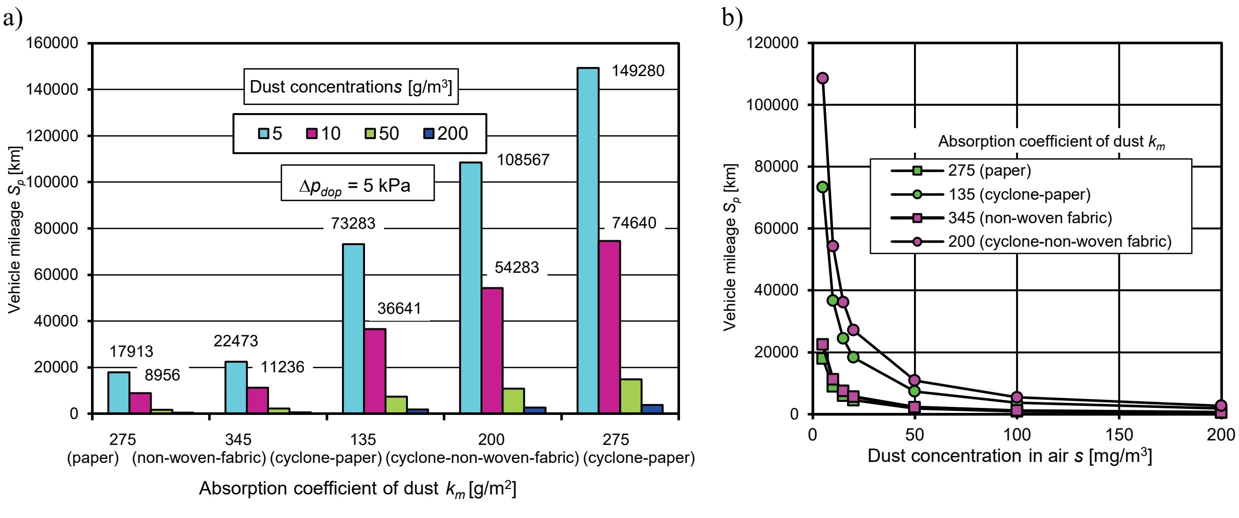

Fig. 9. Predicting the mileage of a vehicle fitted with a single-stage and a two-stage filtration system depending on the: a) absorption coefficient of dust; b) dust concentration

The same filter elements used in a two-stage filtration system (downstream of the multicyclone) after reaching the allowable flow rate Δp_{dop} = 5 kPa show significantly improved vehicle mileage: S_{pII} = 73000 km and S_{pII} = 108000 km, respectively. Better mileage of the vehicle fitted with a non-woven fabric filter element in a single-stage filtration system and a two-stage filtration system is due to the higher thickness of the non-woven fabric (g = 2.34 mm) compared to the thickness of the filter paper (g = 0.56 mm).

Predicting the mileage of the vehicle fitted with a two-stage filtration system (cyclone-panel filter) using the same absorption coefficient of dust k_m as calculated for a single-stage filter will increase the mileage, however it is incorrect, since the actual absorption coefficient of dust k_m is significantly lower. For a vehicle fitted with a filtration system (cyclone-paper), the mileage increases from 73000 km to 150000 km, by 100% (Fig. 9a). It is recommended to determine the actual absorption coefficient of dust k_m for a specific filtration medium, which may in turn be used to determine the actual vehicle mileage. Dust concentration in the inlet air (Fig. 9b) significantly affects the vehicle mileage until reaching the allowable flow rate Δp_{dop}.

The predicted mileage rapidly decreases with the increase in dust concentration s. Twofold increase in dust concentration in air (from 5 mg/m^3 to 10 mg/m^3) will reduce the predicted vehicle mileage by 50%. Operation of a two-stage air filter (multicyclone-paper filter element) of a truck at dust concentration of s = 50 mg/m^3 will give a mileage (at flow resistance Δp_{dop} = 5 kPa) of approx. 7000 km, and only 1800 km at s = 200 mg/m^3 (Fig. 9b).

Special purpose vehicles and military vehicles operate at significantly higher dust concentrations in air (1000 mg/m^3 and over). As a result, proper selection of a suitable filtration system is crucial.

Conclusions

1. The developed methods allow determining the basic characteristics of filter media used as a second filtration stage with any structural parameters and a wide range of changes in the filtration conditions corresponding to the air filter operation at high dust concentrations.
2. The unconventional nature of the methods lays in the fact that the filter medium is subject to dust whose chemical composition and particle size distribution was changed and modified by the actual air filtration process in the cyclone.
3. The absorption coefficient of a filter medium in a “multicyclone-porous filter panel” configuration is twice lower than the absorption coefficient of the same material in a single-stage filtration system, and is affected by the particle – size distribution of the dust. It directly affects the filter service life until reaching the allowable flow rate, and thus vehicle mileage.
4. Low separation efficiency (φ = 55-77%) of the filter medium and large (d_{zmax} = 14 μm) particle size in filtered air in the initial short period of operation may result in an accelerated wear of the pistons, piston rings and cylinder liners.
5. Predicting the mileage of the vehicle fitted with a two-stage filtration system (cyclone-panel filter) using the absorption coefficient of dust k_m calculated for a single-stage filter is incorrect, since it will “artificially” extend the mileage (by up to 100%).
6. Vehicle mileage from the point the filter reaches its allowable flow resistance Δp_{dop} is affected by the absorption coefficient of dust k_m of the filter medium and the dust concentration in the inlet air.

References

[1] Cenrtisep Air Cleaner., *Information materials published by PALL Corporation*, USA 2004.
[2] Das, A., Alagirusamy, R., Nagendra, K. R., *Filtration characteristics of spun-laid nonwoven fabrics*, Indian Journal of Fibre & Textile Research, Vol. 34, pp. 253-257, 2009.
[3] Durst, M., Klein, G., Moser, N., *Filtration in Fahrzeugen*, Mann+Hummel GMBH, Ludwigsburg, Germany, 2005.
[4] Dziubak, T., *Intake air filtration in internal combustion engines of motor vehicles*, Military University of Technology, Warsaw, 2012.
[5] Dziubak, T., *Experimental research of air two stage paper filter of special vehicle engine*, Bulletin of the Military University of Technology, Vol. LIX, No. 3, pp. 129-147, 2010.
[6] Dziubak T., *Study on the process of intake air filtration in internal combustion engines of special vehicles*, Postdoctoral dissertation. Military University of Technology, Warsaw 2008.

[7] Dziubak, T., *Modification of returnable cyclone with a tangent inlet construction*, Bulletin of the Military University of Technology, Vol. LV, No. 2, pp. 279-301, 2006.
[8] Dziubak, T., Szwedkowicz, S., *Operating properties of non-woven fabric panel filters for internal combustion engine inlet air in single and two-stage filtration systems*. Maintenance and Reliability, Vol. 17, No. 4, pp. 519-527, 2015.
[9] Dziubak, T., Szwedkowicz, S., *Experimental research on filtering fibers in a cyclone–porous barrier system*, Combustion Engines, No. 3 (158), pp. 45-55, 2014.
[10] Dziubak, T., Szwedkowicz, S., *Experimental research of filtration paper operating in "cyclone-porous barrier" system*, Bulletin of the Military University of Technology, Vol. LXII, No. 1, pp. 271-286, 2013.
[11] Dziubak, T., Szwedkowicz, S., *Experimental research of axial cyclones of combustion engines air filters*, Bulletin of the Military University of Technology, Vol. LXII, No. 2, pp. 201-217, 2013.
[12] Erdmannsdorfer, H., *Lesttingmoglichkeiten von Papierfiltern zur Reinigung der Ansaugluft von Diselmotoren*, MTZ, 32, No. 4, 1971.
[13] Jaroszczyk, T., Petrik, S., Donahue, K., *Recent development in heavy duty engine air filtration and the role of nanofiber filter media*, Journal of KONES Powertrain and Transport, Vol. 16, No. 4, pp. 207-216, 2009.
[14] Jaroszczyk, T., Fallon, S. L., Schwartz, S. W., *Development of high dust capacity, high efficiency engine air filter with nanofibers*, Journal of KONES Powertrain and Transport, Vol. 15, No. 3, pp. 215-224, 2008.
[15] Jaroszczyk, T., Pardue, B.A., Holm, Ch.E., *Recent advances in engine air cleaners design and evaluation*, Journal of KONES Powertrain and Transport, Vol. 11, No. 1-2, pp. 259-275, 2004.
[16] Jo, Y., Tien, Ch., Ray, M. B., *Development of a post cyclone to improve the efficiency of reverse flow cyclone*. Powder Technology, Vol. 113, (1-2), pp. 97-108, 2000.
[17] Korea Filtration Technologies Co., Performance mill sheet, *Information materials published by WIX Filtron*, Gostyń 2013.
[18] Kothari, V. K., Das, A., Singh S., *Filtration behavior of woven and nonwoven fabrics*. Indian Journal of Fibre & Textile Research 32, pp. 214-220, 2007.
[19] Lim, K. S., Kim, H. S., Lee, K. W., *Characteristics of the collection efficiency for a cyclone with different vortex finder shapes,* Journal of Aerosol Science, Vol. 35, (6), pp. 743-754, 2004.
[20] Melzer, H. H., Brox, W., *Ansauggerauschdampfer und Luftfilter für BMW 524 td*. MTZ, 45 No. 5, pp. 223-227, 1984.
[21] Muller, T. K., Meyer, J., Thebault, E., Kasper, G., *Impact of an oil coating on particle deposition and dust holding capacity of fibrous filters*. Powder Technology, 253, pp. 247-255, 2014.
[22] PN-S-34040, *Filtry powietrza. Wymagania i badania*, PKN, 1996.
[23] Ruzaev, I. G., Strykovskiy, A. R., Osnovnye trebovaniya k sistemam ochistki vozdukha sovremennykh avtomobil'nykh dvigateley, Dvigatelestroenie, No. 3, pp. 23-25, 1983.
[24] Sakthivel, S., Ehzil Anban, J. J., Ramachandran, T., *Development of Needle-Punched Nonwoven Fabrics from Reclaimed Fibers for Air Filtration Applications*. Journal of Engineered Fibers and Fabrics, Vol. 9, (1), pp. 149-154, 2014.
[25] Taufkirch, G., *Papierluftfilter in der Einsatzpraxis von Nutzfahrzeugen*. MTZ, 58 No. 4, pp. 230-238, 1997.
[26] Taufkirch, G., Mayr, G., *Papierluftfilter für Motoren in Nutzfahrzeugen*. MTZ, 45, No. 3, pp. 95-105, 1984.
[27] WIX Filtron, *Catalogue of filters*, Gostyń 2010.
[28] www.retopfibre.en.alibaba, 15.09.2017.

Manuscript received 21 September 2017; approved for printing 10 January 2018