EXPERIMENTAL RESEARCH ON NONWOVEN FILTER FABRIC FOR INTAKE AIR FILTRATION IN THE IC ENGINE OF AN OFF-ROAD VEHICLE

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Summary

In this paper, the properties of filtering media used as porous membranes in air cleaners of modern motor vehicles have been analysed. A relation that defines the air filter life has been presented and a dust absorption coefficient k_m of a filtering medium has been defined. Methods of testing filter elements made of nonwoven filter fabrics and working in conditions corresponding to the primary and secondary air filtration stage have been discussed. Results of examining the filtration efficiency, threshold, and restriction characteristics of the filtering media under consideration have been analysed. The dust absorption coefficient k_m of a nonwoven filter fabric has been determined for the fabric working at different air velocities during the filtration. The impact of the particle size distribution of dust, changed by the intake air pre-treatment in a uniflow cyclone, on the characteristics of the nonwoven fabric under test and on the value of its k_m coefficient has been examined. The benefits gained from two-stage air filtration have been indicated.

Keywords: combustion engines, two-stage air cleaner, filtering media, air filtration efficiency and threshold, filter restriction, dust absorption coefficient

1. Introduction

In modern passenger cars and light goods vehicles, single-stage air cleaners with a porous membrane, being in most cases a filter element made of paper or nonwoven fabric, are used to filter the internal combustion (IC) engine intake air. The engines of heavy goods and special vehicles, including those used for military applications (e.g. tanks, personnel carriers, etc.), are very often operated on sandy roads and in off-road conditions, where the dust concentration in air is particularly high and often exceeds 1 g/m^3. The engines of such vehicles are characterized by high power capacity (over 300 kW) and high airflow requirement (exceeding 1 000 m^3/h). If a motor truck provided with an engine of 1 200 m^3/h

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airflow requirement is operated on dirt roads at a dust concentration in air of s = 0.1 g/m^3 then about 960 g of dust is fed to its air cleaner together with the intake air for 8 h of the vehicle operation. For the intake air quality and vehicle life requirements to be met, heavy goods and special vehicles are provided with two-stage air cleaning systems. The primary filtration stage is built as a mono-cyclone or multi-cyclone unit (inertial air cleaners); a porous membrane, made in most cases as a cylindrical paper filter element, is used as the secondary stage. Materials with nanofibre additives are increasingly often used for the filtration of intake air in IC engines of motor vehicles. "Core-type" filter elements manufactured to the PowerCore technology should be mentioned as innovative solutions. Conversely, any descriptions of the use of nonwoven filter fabrics as the secondary or tertiary filtration stage in multi-stage air cleaners cannot be found in the available literature.

Increasingly stringent users' requirements as regards the durability and reliability of modern motor vehicle engines enforce intensification of research and development work on the filtration of intake air in such engines, aimed at the launching of air cleaners showing the best possible filtration efficiency and threshold, lowest restriction, and longest filter life.

Multi-cyclones are characterized by low restriction, which remains constant for their whole service life at that, relatively high filtration efficiency (about 87% for uniflow cyclones and about 96% for reverse-flow cyclones), and capability of separating significant dust masses from large volumes of the air flowing through [7]. Various grades of filter paper offer very good filtration efficiency and threshold but they have low dust absorption coefficient, which does not exceed 220 g/m^2 [1–3, 5, 20]. Nonwoven filter fabrics show slightly worse filtration efficiency and threshold as against those of paper but are characterized by much higher dust absorption coefficient [2, 4, 19].

The available Polish and foreign literature does not provide information about the characteristics of nonwoven fabrics intended for intake air filtration in IC engines. In particular, the literature does not offer any data on the dust absorption coefficient of nonwoven fabrics used for the primary or secondary intake air filtration stages in such engines. No information has been published, either, about the impact of the particle size distribution of dust on the characteristics of nonwoven filter fabrics, especially on their dust-holding capacity. Thanks to the cyclone's properties that cause dust particles of bigger size and mass to be arrested, the size distribution of the dust carried by the air that has gone through the cyclone is changed. In consequence, the dust particles reaching the filtering membrane are much smaller than they would be if the dust were sucked in directly from the environment. The data presented in [3, 5, 6] show that the dust-holding capacity of filter paper is significantly reduced when the paper arrests dust of small particle size (< 25 μm).

All the above shows the advisability of research work that would make it possible to obtain information necessary for correct determination of the filter life where the function of a porous membrane is fulfilled by an element made of nonwoven filtering fabric and working in conditions such as those of the secondary filtration stage, i.e. situated downstream of the inertial air cleaner.

2. Characteristics of two-stage air cleaners

In the conditions of high dust concentration in air, multi-stage air cleaners are used, which consist of air cleaners of different filtration efficiency and restriction connected in series. The primary filtration stage is an inertial air cleaner (mono-cyclone or multi-cyclone) and the secondary filtration stage, situated downstream of it and connected with it in series, is a porous membrane made in most cases as a cylindrical filter element or a system of several such elements connected in parallel with each other [4, 6].

Multi-cyclones can separate significant dust masses from large volumes of the air flowing through, at low restriction (of the order of 2–3 kPa), which remains constant for their whole service life at that, filtration efficiency of up to 96%, filtration threshold of 15–35 μm, and capability of unattended operation in the case of automatic dust removal from the dust bin [1, 3]. The "multi-cyclone with porous membrane" air cleaner systems are characterized by high efficiency (up to 99.9%) of the separation of mineral dust [1]. However, a considerable flaw in such systems is their high empty mass with large overall dimensions. Their life is limited by the rate of growth in the restriction of the membrane element.

The filtering membranes of IC engine intake air filters in motor vehicles are predominantly made of filter paper, manufactured by specialized companies in many grades that differ from each other in structural features and such technical specifications as basis weight, thickness, air permeability, pore dimensions, breaking strength, and bursting strength.

The filter paper is processed into pleated web (Fig. 1a), from which filter elements may be set up in various ways. In most cases, filter elements are made in the form of cylinders with circular or oval cross-section (Fig. 1b) or panels (Fig. 1c) [1, 2, 9, 21, 22].

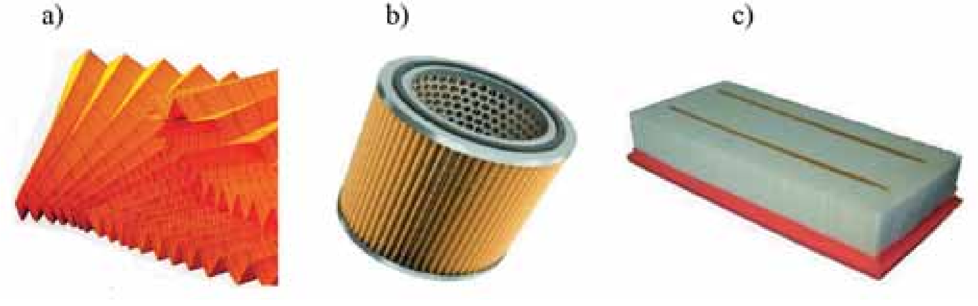

Fig. 1. Filter element shapes: a) pleated web; b) cylindrical element; c) panel-shaped element

A characteristic feature of modern filter elements and air cleaners is axial airflow, thanks to which turbulences can be avoided and, due to direct flow of the aerosol to the air cleaner outlet, the filter restriction is minimized. An example of such a solution is the filter element design known under the name "PowerCore" and developed by the Donaldson Company. The filter elements made to the PowerCore technology are built in the form of a core made by placing plain and pleated paper layers alternately on each other (Fig. 2a). The passages thus formed are alternately closed at one end in such a way that if a passage is open at the inlet end then it is closed at the outlet end and vice versa. Such a design forces the air to flow through the filtering medium to the adjacent passage (Fig. 2b).

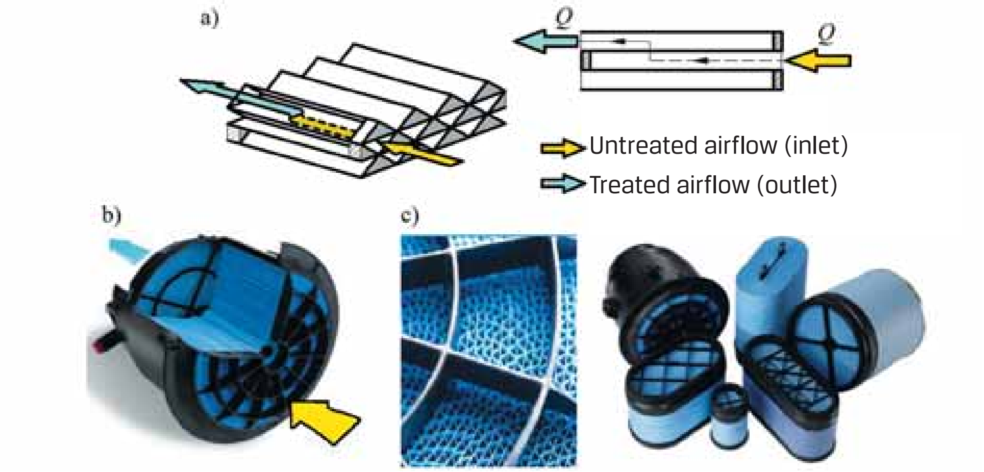

Fig. 2. PowerCore filter element [17]: a) principle of operation of the filter element; b) airflow direction; c) front-end view of the filter element; d) examples of filter element shapes

The filter elements manufactured to the PowerCore technology have 2–3 times smaller overall dimensions in comparison with those of the corresponding elements based on pleated filter paper made traditionally; at the same time, the efficiency of the former exceeds that of an average traditional filter (φ_f = 99.99% as against φ_f = 99.85%, respectively) [17, 18].

The filter paper membranes are increasingly often built with a nanofibre layer being additionally applied. Nanofibres are usually meant as fibres with a diameter less than 1 μm, which are made with the use of the "electrospinning" method [10, 11, 14] or the "meltblown" process [15]. Nanofibres of about 50–500 nm diameter are used for the filtration of intake air in motor vehicle engines.

The nanofibre properties significantly differ from the properties of cellulose fibres used in standard filters.

In consideration of limited mechanical properties of a thin nanonet layer, this material is applied to a base layer of conventional filtering media, which have higher strength and make it possible for such a material to be machined (Fig. 3).

Nanofibres may be applied to one side or both sides of the base material, which may be polyester, nylon, or paper. The nanonet applied to a base material with large pores arrests small particles, especially the dust particles with a size of below 5 μm (Fig. 4), without significant increase in the pressure drop across the filtering membrane [11].

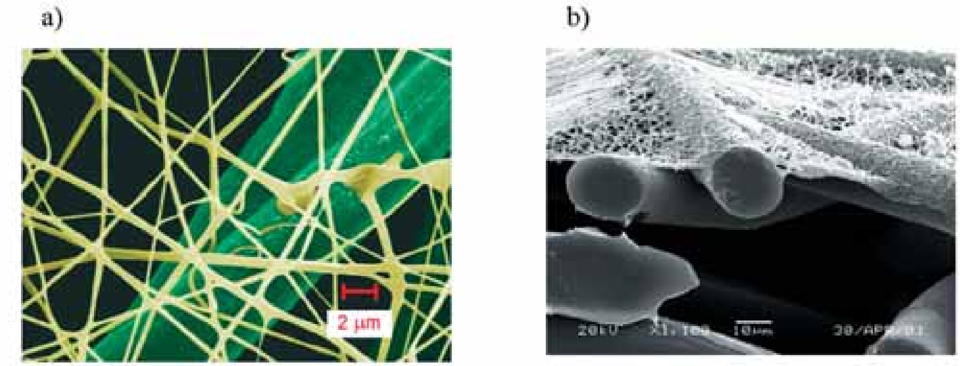

Fig. 3. Nanonet applied to a base made of cellulose fibres with diameters of about 10 µm: a) top view [19]; b) cross-section (nanofibre diameters of about 250 nm) [12]

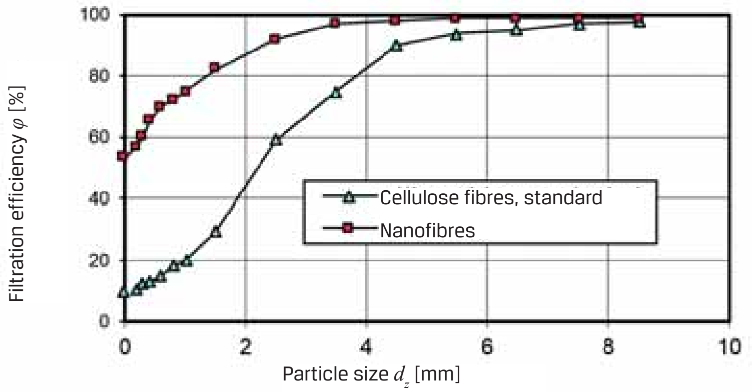

Fig. 4. Filtration efficiency of a base made of cellulose fibres with standard diameters and of nanofibres, as used in the air filters of the Abram tanks [11]

The membrane-type air filter elements for passenger cars, especially for those made in Asia (Japan, South Korea), are increasingly often manufactured with the use of nonwoven filter fabrics. The filtering media of this kind have twice as high basis weight, several times bigger thickness, and definitely lower stiffness in comparison with filter papers [8, 13]. Modern nonwoven filter fabrics have gradient structure, with the fibre packing density increasing in the airflow direction (Fig. 8). The technical specifications of nonwoven filter fabrics manufactured by Korea Filtration Technologies Co. have been presented in Table 1.

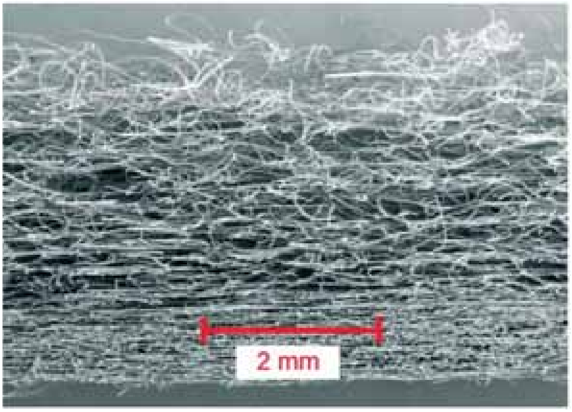

Fig. 5. Nonwoven filter fabric with increasing fibre packing density [19]

Table 1. Technical specifications of nonwoven filter fabrics manufactured by Korea Filtration Technologies Co. [13]

Nonwoven fabric grade	**Basis weight**	**Thickness**	**Air permeability**	**Tensile strength**	**Bending strength**	**Bursting strength**
	$[g/m^2]$	**[mm]**	**$[cm^3/cm^2/s]$**	**[N/50 mm]**	**[N/30 mm]**	**[MPa]**
AC-1800	290	2.8-3.6	50-85	>98	1.96-3.62	0.49
AC-3800	240	3.15-3.85	65-90	>98	1.96-3.62	0.39
AC-3421	230	2.43-2.97	55-70	>147	1.47-2.94	0.59
AC-303	250	2.7-3.3	75-95	>98	1.47-2.25	0.59
AC-301	210	2.43-2.86	80-110	>98	1.47-2.94	0.59
AC-510	205	2.7-3.3	90-140	>98	1.47-2.94	0.49
AC-180	300	2.61-3.19	45-60	>196	1.47-3.43	0.78
AC-250P/C	270	2.7-3.6	55-70	>98	1.47-2.94	0.78
AC-250G	270	2.88-3.52	55-75	>98	1.47-2.94	0.78
Bursting strength	ASTM D 6242-1998	ASTM D 5729-1997	ASTM D737-1996	ASTM D 5053-1995	ASTM D 5732-1995	ASTM D 3786-2001

Due to low stiffness of pleats made of nonwoven filter fabrics, the construction of traditional air filter elements based on filtering media of this type is a dubious issue, especially if pleats of significant height are made of particularly long fabric web (Fig. 6a). This problem is solved by setting the pleated nonwoven fabric in a rigid plastic frame (Fig. 6b).

Fig. 6. Forms of nonwoven fabric filter elements: a) pleated web; b) element made as pleated nonwoven fabric set in a rigid frame; c) element made as a panel-shaped moulding

The filter elements thus made have small dimensions and they are used in passenger cars. Another solution adopted to raise the stiffness of nonwoven synthetic fabrics is the pleating of such fabrics together with special plastic mesh, thanks to which the element is protected from damage during operation [8]. Panel-shaped filter elements made of nonwoven fabrics by wet moulding (Fig. 6c) have recently become popular, too, and they find application in air filters of passenger cars.

The filter performance is described by the following parameters:

- filtration efficiency – the ratio of mass m_p of the dust arrested by the filter to mass m_d of the dust fed to the filter:

$$\varphi = \frac{m_p}{m_d} \cdot 100\% , \tag{1}$$

- restriction (resistance to airflow) – the difference between total pressures upstream p_1 and downstream p_2 of the filter:

$$\Delta p_f = p_1 - p_2 , \tag{2}$$

- filtration threshold – the maximum dust particle size d_{zmax} in the air downstream of the filter.

- dust-holding capacity – the mass Δm of the dust that will be arrested by the filter before the adopted maximum acceptable restriction value (adopted as 200 % of the restriction for the clean filter at nominal airflow rate) is reached [16].

The filter life until the adopted maximum acceptable restriction value Δp_{fdop} is reached depends not only on the parameters of the airflow filtration process at the filtering membrane but also on the dust-holding capacity of the membrane, which is determined by the membrane structure and, on the other hand, on the size of the dust particles arrested [3, 4, 5]. The life τ of a two-stage air cleaner may be determined from the following empirical equation [1, 3]:

$$\tau = \frac{F_c \cdot k_m \cdot k_c}{Q_{\max} \cdot s \cdot (1-\varphi_M) \cdot \varphi_w} \ \text{[h]}, \tag{3}$$

where: F_c – area of the filtering medium of the secondary filtration stage [m^2];
k_m – dust absorption coefficient of the filtering medium for the adopted maximum acceptable restriction value Δp_{fdop} [g/m^2];
k_c – coefficient making it possible to take into account the difference between the characteristics of test dust and real dust particles;
Q_{max} – nominal airflow requirement of the engine [m^3/h];
s – dust concentration in the air sucked in by the engine [g/m^3];
φ_M – filtration efficiency of the primary filtration stage;
φ_w – filtration efficiency of the filter element..

For the time between replacement (service life) of an air cleaner in specific operation conditions to be determined, the dust-holding capacity of the filtering medium, defined by its dust absorption coefficient k_m, must be known. The information published by filtering media manufacturers is limited to details describing the structure of their products while the data concerning the filtration properties of such materials, especially the dust absorption coefficient k_m, are hardly available. Filtration characteristics are determined during empirical research, based on standard test procedures. The k_m coefficient value is determined (with assuming uniform dust distribution over the whole active area of the filtering medium) from the following equation:

$$k_m = \frac{m_{cw}}{F_w} \ \text{[g/m}^2\text{]}, \tag{4}$$

where: m_{cw} – total mass of the dust arrested by the filter element, for the adopted value of the maximum acceptable restriction Δp_{fdop} [g];
F_w – active area of the filtering medium.

According to data available from Polish and foreign literature, the values of dust absorption coefficient k_m, determined for various filter paper grades with the use of standard test dust, reach a level of up to 220 g/m^2 [1–3, 5]. The dust-holding capacity of modern nonwoven filter fabrics with gradient structure is much higher than that of filter papers, ranging from 0.9 kg/m^2 to 1.1 kg/m^2 [2]. The high dust-holding capacity of nonwoven filter fabrics results from the fact that such fabrics are three times as thick as the papers.

In two-stage intake air cleaning systems of IC engines, the filter element receives dust that is free from particles with a size of more than 15–25 μm, as the size distribution of the dust is changed by the intake air pre-treatment at the primary air filtration stage (in a monocyclone or multi-cyclone). This has a critical impact on the filtration process that takes place in the porous membrane because, in particular, the filter restriction growth is thus intensified and, in consequence, the filter life limited by reaching the maximum acceptable restriction value Δp_{fdop} is shortened.

To determine the actual time of operation of a two-stage air cleaner until the maximum acceptable restriction value Δp_{fdop} is reached, one must know to what extent the change in the dust size distribution caused by the intake air pre-treatment in the inertial air cleaner affects the dust-holding capacity of the filtering medium.

An answer to such a question may be obtained from experimental tests of complete two-stage air cleaners with the use of the test stands and research methods available. For vehicle air cleaners operating at high airflow requirement, such tests are costly and labour-consuming, with significant amounts of test dust being needed. The method presented in publications [5, 6] makes it possible to carry out such tests with the time and costs being considerably reduced. At the works described there, a single reverse-flow cyclone with tangential inlet [5] or uniflow cyclone [6] was used as the primary filtration stage; as the secondary one, a porous membrane was used with its active area having been proportionally reduced to a size that ensured the adequate air filtration velocity to be maintained. A similar method was employed at the work described in [21], where a specially designed small mono-cyclone was used as the primary filtration stage.

However, no information is available about the impact of the particle size distribution of the dust having been pre-treated by an inertial air cleaner on the dust absorption coefficient of nonwoven filter fabrics. Therefore, the carrying out of appropriate tests that would make it possible to determine the impact of particle size distribution of dust on the value of the dust absorption coefficient of nonwoven filter fabrics is recommendable.

3. Objectives and scope of the tests

The tests were carried out to obtain filtration characteristics of the nonwoven filter fabric under examination, operating as a single-stage filter and in conditions corresponding to the secondary filtration stage downstream of a uniflow cyclone, and to determine the dust absorption coefficient km of the fabric. The material tested was nonwoven filter fabric AC 301 manufactured by Korea Filtration Technologies Co. (Table 4) and formed into cylindrical filter elements.

Within the tests, the filtration efficiency, filtration threshold, and filter element restriction were determined as functions of the dust absorption coefficient km (for mass m_z) and mass md of the test dust fed to the system, with the PTC D dust grade (a Polish equivalent to the standard AC Fine dust) being used as the test dust:

- filtration efficiency $\varphi_w = f(k_m)$, $\varphi_w = f(m_d)$,
- filtration threshold $d_{zmax} = f(k_m)$, $d_{zmax} = f(m_d)$,
- filter restriction $\Delta p_w = f(k_m)$, $\Delta p_w = f(m_d)$.

Table 2. Technical specifications of the nonwoven filter fabric under test [13]

Description	Unit	Value
Basis weight	[g/m^2]	210±10 %
Thickness	[mm]	2.34–2.86
Air permeability	[cm^3/cm^2/s]	80–110 at 120 Pa
Tensile strength	[N/50 mm]	›98
Bending strength	[N/30 mm]	1.47–2.94

The characteristics were determined for the nonwoven filter fabric working in the conditions of operation of a single-stage filter and for the fabric working downstream of an inertial air cleaner, i.e. a uniflow cyclone, at three characteristic air filtration velocities:

- υ_{F1} = 0,08 m/s – air filtration velocity typical for filter papers;
- υ_{F3} = 0,27 m/s – air filtration velocity close to that specified (by Mann+Hummel) as the maximum value acceptable for nonwoven filter fabrics;
- υ_{F2} = 0,17 m/s – intermediate air filtration velocity.

The nonwoven filter fabric working in the single-stage filtration conditions was tested at an airborne dust concentration of s = 0.5 g/m^3, ; for the nonwoven fabric operating downstream of a uniflow cyclone, the dust concentration at the cyclone inlet was set at s = 1 g/m^3. As the test dust, the PTC D dust grade was used, which is a Polish equivalent to the standard AC Fine dust. The chemical composition and particle size distribution of the test dust has been specified in Polish Standard PN S 34040 [16].

The nonwoven filter fabric working in conditions corresponding to the secondary filtration stage was tested with the use of a system where the dust separated by the cyclone was continuously sucked off (i.e. removed from the dust bin) by ejection. The dust suction ratio, defined as the ratio of the flow rate of the air sucked from the dust bin to the flow rate of the air leaving the cyclone outlet (clean air), was set at m_0 = 10%.

4. Method and conditions of testing the nonwoven filter fabric

To determine the value of the dust absorption coefficient k_m, one must know the mass of the dust that has to be arrested by 1 m^2 of nonwoven filter fabric for the filter restriction Δp_{fdop} to build up to the maximum acceptable level adopted. The method taken from publications [3, 5, 6] makes it possible to determine the k_m coefficient and the filtration characteristics of a sample of nonwoven filter fabric prepared in the form of a test filter element capable of operating in conditions corresponding to both the primary and secondary filtration stage.

The tests were carried out on a test stand (Fig. 10), the main component of which was a filtration unit composed of a single uniflow cyclone, which was a part of the multi-cyclone of a motor truck's air cleaner, and a cylindrical test filter element made of the nonwoven filter fabric under test and situated downstream of the cyclone, connected with it in series. The test filter element was encapsulated in an airtight metal housing, to which an air and dust feeding tube was connected. The test dust was fed directly onto the filter element. When the nonwoven fabric was tested in the conditions of two-stage filtration, the air and dust feeding tube was replaced with a uniflow cyclone complete with a dust bin body. The construction of the test filter element was based on an AP 019 filter element manufactured by WIX Filtron, with the number of pleats and, consistently, the filtering medium area being changed.

The active area F_W of the nonwoven fabric under test was so selected that the air filtration velocity at the maximum value Q_{Gmax} of the airflow leaving a single cyclone, defined by the equation below (5), did not exceed the maximum air filtration velocity value specified by Mann+Hummel as υ_F = 0.33 m/s [2]:

$$Q_{G\max} = \frac{Q_{sil\max}}{n}, \tag{5}$$

where: Q_{silmax} – maximum engine's airflow requirement;

n – number of cyclones in the complete multi-cyclone.

An important component of the measuring stand is a Pamas 2132 particle counter. It makes it possible to record the number and size distribution of dust particles in the airflow downstream of the test filter element, within the range of 0.7–100 µm divided into 32 measuring sub-ranges limited by minimum and maximum particle diameters ($d_{zmin} \div d_{zmax}$). The sub-range widths may be arbitrarily programmed. The instrument sensor is designed for operation at dust concentrations not exceeding s = 0.25 g/m^3. To analyse the size distribution of the dust particles present in the airflow, the particle counter uses the phenomenon of scattering a laser beam of 680 nm wavelength. The number of counts in a measuring cycle may be arbitrarily programmed. The measurement results are presented in the form of tables where the limits of individual measuring sub-ranges and the numbers of dust particles with size falling within the limits of specific sub-ranges are specified. The results may be supplemented with a table presenting the average numbers of particles falling within individual sub-ranges from all the counts of a specific measuring cycle. The measuring probe of the particle counter is situated in the centreline of the measuring tube at an appropriate distance downstream of the test filter element and the probe inlet is directed against the oncoming airflow Q_G.

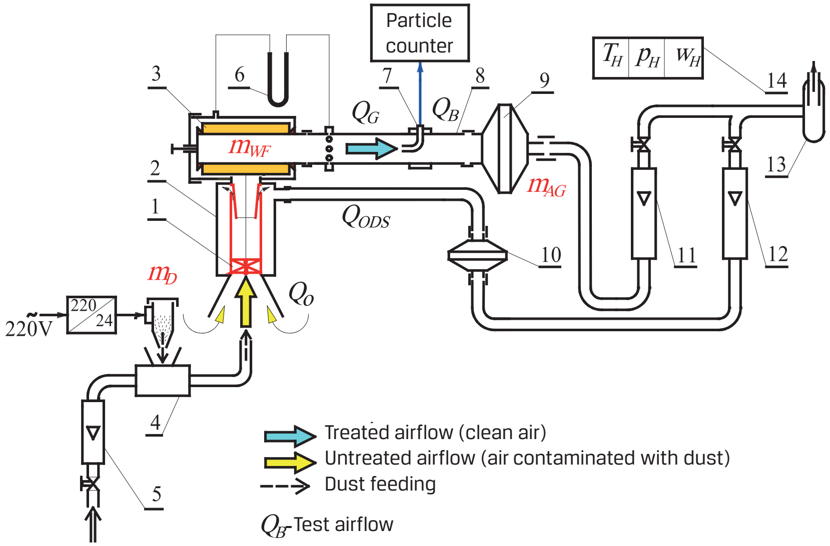

Fig. 7. Functional diagram of the stand for testing nonwoven filer fabrics in the "cyclone-membrane" system: 1 – cyclone; 2 – dust bin; 3 – filter element under test; 4 – dust feeding system; 5 – compressed air rotameter; 6 – liquid manometer; 7 – measuring tube; 8 – dust probe; 9 – absolute filter of the main airflow line; 10 – absolute filter of the suck-off airflow; 11 – main airflow rotameter; 12 – suck-off airflow rotameter; 13 – exhaust fan; 14 – barometer, thermometer and hygrometer unit

The other components of the test stand included dust feeding system, U-tube liquid manometer, RIN float-type rotameters used for test airflow control purposes, barometer, thermometer and hygrometer unit making it possible to determine the air pressure, temperature, and humidity, and absolute filters protecting the rotameters from dust penetration.

The filtration characteristics of the nonwoven filter fabric under test were determined gravimetrically at successive measuring cycles with a pre-defined cycle duration time of τ = 3 min during the initial filter element operation period and τ = 6 min when the filtration efficiency φ_w has become stabilized. The particle size distribution and, thereby, the filtration threshold d_{zmax} was measured during the last minute of duration of a specific measuring cycle.

5. Analysis of test results

The results of determining experimentally the filtration efficiency $\varphi_w = f(k_m)$, filtration threshold $d_z = f(k_m)$, and restriction $\Delta pw = f(k_m)$ (as functions of the dust absorption coefficient km) of the filter element working in the conditions of operation of a single-stage air cleaner and in the filtration conditions corresponding to the secondary filtration stage, downstream of the uniflow cyclone at three different air filtration velocities v_F, have been presented in Figs. 8 and 9.

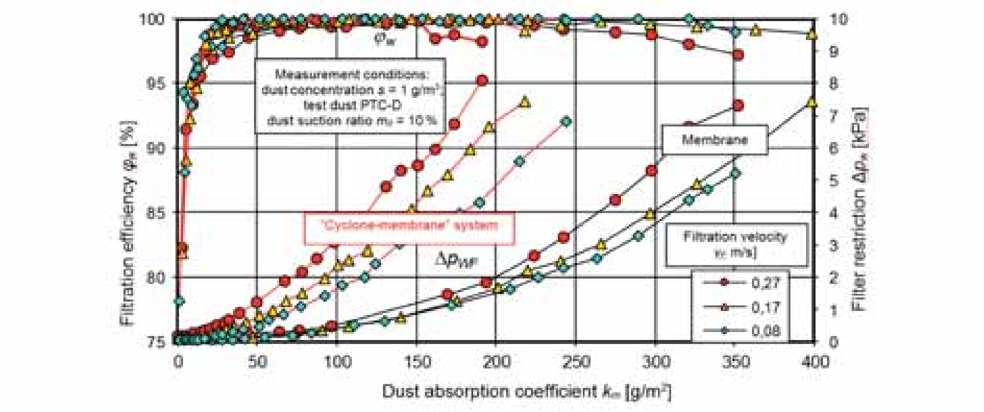

Fig. 8. Filtration efficiency $\varphi_w = f(k_m)$ and filter restriction $\Delta p_w = f(k_m)$ as functions of the dust absorption coefficient k_m for the filter element working in the single-stage filtration conditions and in the conditions corresponding to the secondary filtration stage, downstream of the uniflow cyclone

The filtration efficiency φw and filter restriction Δp_w of the nonwoven fabric under test increase with growing mass m_z of the dust arrested by the filter element and, consistently, with growing dust absorption coefficient k_m of the filter. In the initial period of operation of the filter element, the filtration efficiency rapidly rises. In literature, this period, extending from the beginning of filter element operation until the moment of the filtration efficiency of the filtering medium becoming stable, is commonly referred to as transient filtration period. It is followed by a steady filtration period, characterized by high filtration efficiency exceeding φ_w = 99% and very slow increase in this value. The filtration efficiency φ_w, filtration threshold d_{zmax}, and restriction Δp_w curves obtained for the filter elements working in the conditions of operation of single-stage and two-stage air cleaners are similar to each other in terms of their shape but different in terms of their values.

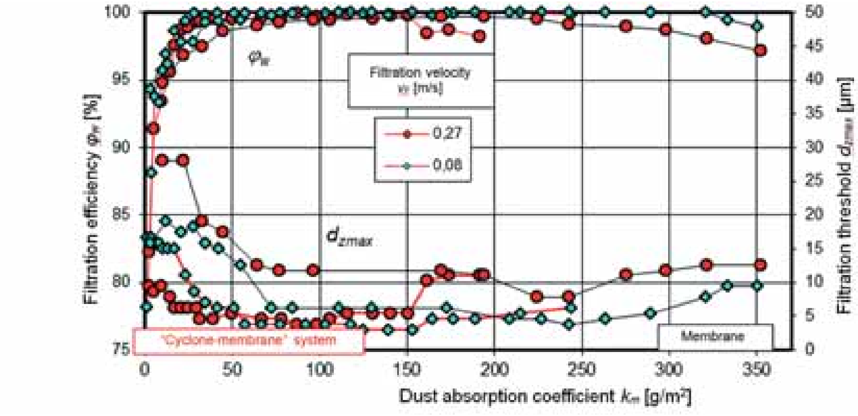

Fig. 9. Filtration threshold $d_{zmax} = f(k_m)$ and filtration efficiency $\varphi_w = f(k_m)$ as functions of the dust absorption coefficient k_m for the filter element working in the single-stage filtration conditions and in the conditions corresponding to the secondary filtration stage, downstream of the uniflow cyclone

For the nonwoven fabrics under test, the steady filtration period was assumed to begin when the filtration efficiency reached a level of φ_w = 99.5%. The initial filtration efficiency determined after the first measuring cycle for the nonwoven fabrics operating in the single-stage filtration conditions was about φ_w = 95%. The same material, when receiving dust passed by the uniflow cyclone, showed slightly lower filtration efficiency values at similar dust absorption coefficient k_m. This is connected with the particle size distribution of the dust received by the material. However, when this coefficient just exceeded the level of k_m = 15 g/m^2, the filtration efficiency of the nonwoven fabric operating as the secondary filtration stage was higher than that of the fabric working in the single-stage filtration conditions.

For the nonwoven fabric that received dust of standard particle size distribution, the assumed filtration threshold of φ_w = 99.5 % was achieved at the dust absorption coefficient k_m = 72–91 g/m^2, depending on the filtration velocity varying within the range of v_F = 0.08–0.27 m/s. For the fabric working as the secondary filtration stage downstream of the uniflow cyclone, the filtration threshold of φ_w = 99.5 % was achieved at the coefficient value of k_m = 25–30 g/m^2.

In the initial period of operation of the filter element in the conditions corresponding to those of a single-stage air cleaner, the maximum diameters of the dust particles that passed through the filter were d_{zmax} = 15–28 μm, with the higher values being observed at higher filtration velocities. For the filter element working in two-stage filtration conditions, the maximum diameters of the dust particles that passed through the element in the initial period of filter operation were much smaller, i.e. d_{zmax} = 4.6–9.4 μm at 0.27 m/s filtration velocity and d_{zmax} = 6.2–16.6 μm at 0.27 m/s filtration velocity. This was caused by the fact that the dust leaving the cyclone was free from most particles with a size exceeding 15–20 μm. The tightening up of the filtration threshold of the "cyclone and porous membrane" air cleaning system with increasing filtration velocity was related to the performance characteristics of the cyclone used, i.e. increasing filtration efficiency and tightening filtration threshold with increasing airflow [7].

With growing mass of the dust collected on the filter element, the maximum diameters d_{zmax} of the dust particles that passed through the element decrease and stabilize on a level of d_{zmax} = 5–7 μm for the nonwoven fabric operating downstream of the uniflow mini-cyclone and d_{zmax} = 6.2–11.8 μm when the dust is fed directly (without pre-treatment) onto the fabric. This means the beginning of the main period (II) in the filter element service life. The time of duration of this period depends on filtration velocity and this period comes to an end at the moment of sudden worsening of the filtration threshold and efficiency. Thus, the main period is followed by period III, during which the filtration efficiency gradually declines and the size of the largest dust particles occurring in the airflow downstream of the filter element under test is increasing.

For the nonwoven fabrics under test, the transition from period II to period III has been defined as the instant when the filtration efficiency of the material becomes equal to φ_w = 99.5%. In the case of the nonwoven fabric under test operating in the conditions of single-stage filtration with a filtration velocity of v_F = 0.27 m/s, this boundary value was reached at a dust absorption coefficient of k_m = 240.5 g/m^2. The lower filtration velocity, the higher value of the k_m coefficient at which the filtration efficiency begins to decline (indicating the beginning of period III of the filter element service life). At filtration velocities of v_F = 0.17 m/s and v_F = 0.08 m/s, the values of this coefficient were k_m = 297.3 g/m^2 and k_m = 350.5 g/m^2, respectively [8].

During tests of the nonwoven fabric operating downstream of the cyclone, the beginning of a decline in the filtration efficiency was observed to take place when the values of this coefficient reached k_m = 155 g/m^2 at v_F = 0.27 m/s and k_m = 208 g/m^2 at v_F = 0.17 m/s. At the lowest filtration velocity (v_F = 0.08 m/s), the filtration efficiency was not observed to decline to the level of φ_w = 99.5% having been adopted.

The intensity of growth in the filter restriction Δp_w increased with growing filtration velocity vF in both the single-stage and two-stage filtration conditions. The most intensive growth in the filter restriction was observed at the filtration velocity of v_F = 0.27 m/s and this growth was least intensive at the filtration velocity of v_F = 0.08 m/s, which was consistent with the general conditions of flow through a porous membrane. It is the filter resistance that limits the air filter service life. In the vehicle operation conditions, the maximum acceptable filter restriction is specified by filter manufacturers as 5–7 kPa, depending on the air filter and vehicle type. During the tests, the maximum values of dust absorption coefficient k_m of nonwoven filter fabrics were determined at a filter restriction of Δp_w = 5 kPa.

It can be seen in Fig. 8 that for the nonwoven fabric operating as the secondary filtration stage, the dust absorption coefficient values were lower by about 50 % than those for the fabric operated as the primary stage of filtration of the airflow contaminated with dust of standard particle size distribution. In the latter conditions, the maximum values of the dust absorption coefficient were k_m = 290 g/m^2 at v_F = 0.27 m/s, k_m = 330 g/m^2 at v_F = 0.17 m/s, and k_m = 343 g/m^2 at v_F = 0.08 m/s. When dust with particle size distribution having been changed by the cyclone was fed to the nonwoven fabric, these values were lower, i.e. they were k_m = 135 g/m^2 at v_F = 0.27 m/s, k_m = 164.3 g/m^2 at v_F = 0.17 m/s, and k_m = 203.2 g/m^2 at v_F = 0.08 m/s. For filter papers, the maximum values of the dust absorption coefficient measured at a filtration velocity close to that of the nonwoven fabrics under test, i.e. v_F = 0.06 m/s, were found to be much lower and they did not exceed 40 g/m^2, according to the research work described in [3].

The reduction in the maximum value of the dust absorption coefficient of the nonwoven fabric operating as the secondary filtration stage downstream of the uniflow cyclone with axial flow may be explained by the fact that the dust having gone through the cyclone is free from the largest particles with a size of more than d_{zmax} = 15–20 μm and this has an impact on the conditions of operation of the filtering membrane. Dust particles with small dimensions much easier penetrate the filtering media and more tightly fill the material than larger particles do. The free spaces between dust agglomerates built up from fine particles are smaller than those left in the material in the case of large dust particles and this results in higher aerosol flow velocities and, in consequence, in increased resistance to the flow (i.e. filter restriction).

The use of inertial air cleaners as the primary filtration stage results in a more intensive growth in the filter restriction and in a reduction in the maximum dust absorption coefficient k_m of the nonwoven filter fabric, which significantly reduces the filter service life. This might suggest that the use of the "inertial air cleaner with porous membrane" filtration systems would be ineffective.

However, an analysis of the curves of filtration efficiency and filter restriction vs. total mass of the dust fed together with air to the air cleaner (Fig. 10) shows that the time of air cleaner operation until the maximum acceptable restriction value Δp_{fdop} = 5 kPa is reached for the nonwoven fabric working in the "cyclone and porous membrane" system is almost three times as long (regardless of filtration velocity) as that for the filter element receiving dust directly from the environment.

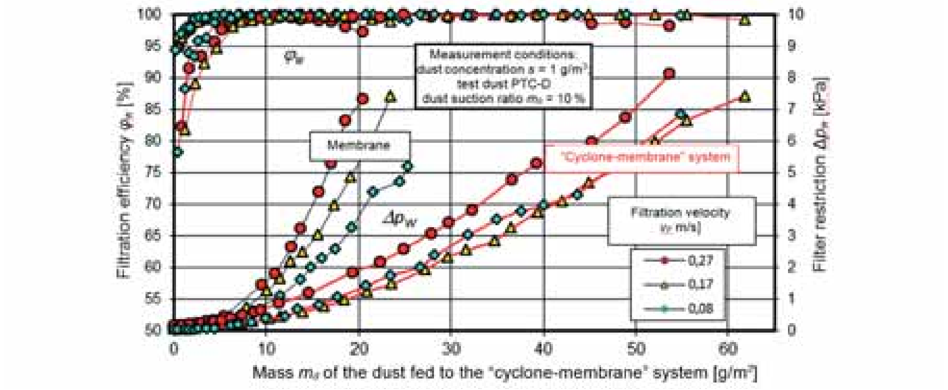

Fig. 10. Filtration efficiency $\varphi_w = f(m_d)$ and filter restriction $\Delta p_w = f(m_d)$ of the nonwoven filter element as functions of mas m_d of the dust fed to the air cleaner system

This may be explained as follows. Since a two-stage "cyclone with porous membrane" filtration system was used, an overwhelming majority of the dust (about 87 % in the case of the air cleaner system under test) was separated from the airflow by the primary filtration system. Hence, as little as 13 % of the total mass of the dust fed to the filtration system under test reached the filter element.

Thus, the service life of the filter element used as the secondary filtration stage was extended by more than 100% (regardless of the filtration velocity.

Figs. 11–14 show changes in the particle size distribution of the dust in the airflow downstream of the filter element under test, operating in two-stage filtration conditions, at a filtration velocity of v_F = 0.08 m/s, in characteristic measuring cycles corresponding to periods I and II of the filter element operation. The particle size distribution has been presented in the form of percentages U_{p_i} of dust particles of individual size groups, determined from the equation:

$$Up_i = \frac{N_i}{N} = \frac{N_i}{\sum_{i=1}^{32} N_i}, \tag{6}$$

where: N_i – number of dust particles of the ith particle size range;
N – total number of dust particles downstream of the filter element.

Simultaneously with an increase in the mass of the dust arrested on the test filter element operating in either single-stage or two-stage filtration conditions, regular growth was observed in the percentage of small dust particles (below d_{zmax} = 1.4 μm) in the airflow downstream of the filter element. During the measuring cycle No. 1, the percentage of these particles downstream of the filter element operating as the secondary filtration stage, at the filtration velocity of υ_F = 0.08 m/s, was U_{p1} = 34.38%, while it grew to U_{p5} = 68.12% during measuring cycle No. 5. During measuring cycle No. 8, which corresponds to the period of steady operation of the filter element, the percentage of particles smaller than d_{zmax} = 1.4 μm in size was U_{p8} = 89.48 % and then it remained on this level till the end of the filter element service life (it was U_{p14} = 90.49 % during measuring cycle No. 14). On the other hand, a rapid drop was noticed in the percentage of larger particles. As an example, the percentage of particles with diameters of d_{zmax} = 2.2–3 μm was U_{p1} = 18.32 % during measuring cycle No. 1, while during measuring cycle No. 14, the percentage of all the particles with diameters exceeding d_{zmax} = 2.2 μm totalled merely U_{p14} = 1.34 %.

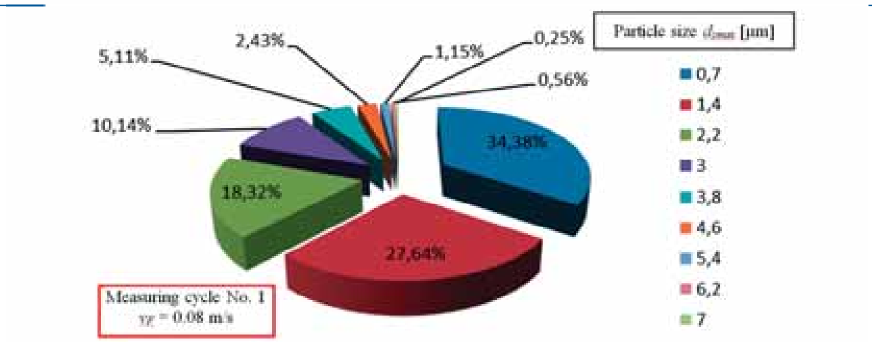

Fig. 11. Particle size distribution of the dust downstream of the test filter element operating in the two-stage filtration conditions: measuring cycle No. 1, filtration velocity υ_F = 0.08 m/s

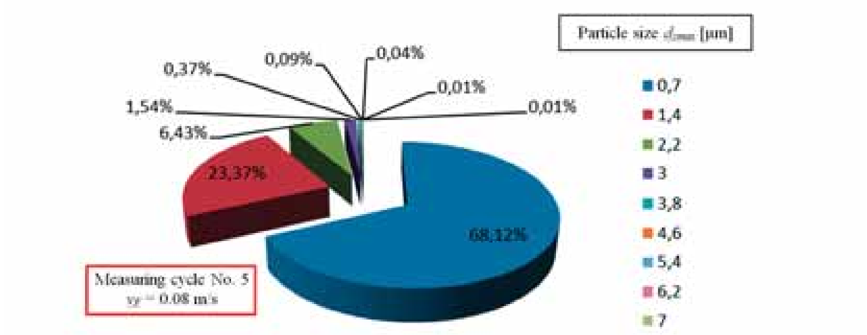

Fig. 12.Particle size distribution of the dust downstream of the test filter element operating in the two-stage filtration conditions: measuring cycle No. 5, filtration velocity υ_F = 0.08 m/s

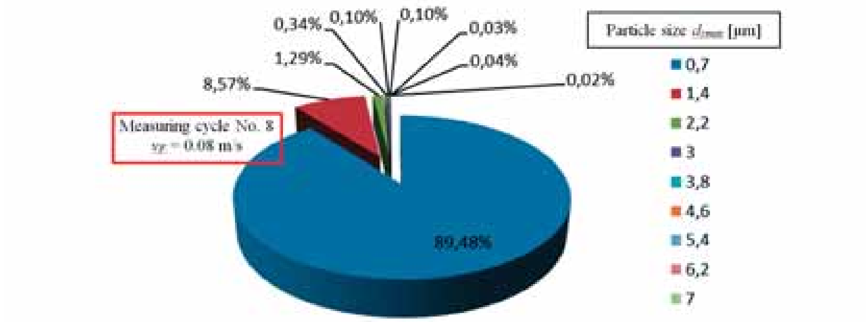

Fig. 13. Particle size distribution of the dust downstream of the test filter element operating in the two-stage filtration conditions: measuring cycle No. 8, filtration velocity υ_F = 0,08 m/s

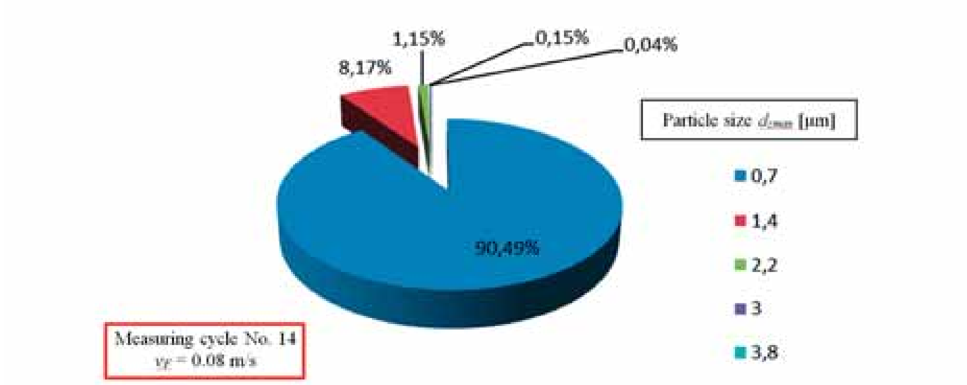

Fig. 14. Particle size distribution of the dust downstream of the test filter element operating in the two-stage filtration conditions: measuring cycle No. 14, filtration velocity υ_F = 0,08 m/s

An analysis of the particle size distribution of the dust downstream of the filter element shows a re-growth in the percentage of particles with larger diameters. This was caused by a "puncture" of the filter element and by the fact that the dust particles that had been previously arrested were carried away by the aerosol flow.

Conclusions

1. The maximum dust absorption coefficient k_m of the nonwoven filter fabric operating as the secondary filtration stage downstream of a uniflow cyclone, determined in accordance with the method presented, i.e. at the instant when the filter restriction reaches a value of Δp_w = 5 kPa for filtration velocities from within the range of v_F = 0.08–0.27 m/s, takes values of k_m = 203–135 g/m^2, respectively. These values are several times as high as those determined for filter papers in similar conditions, which may be chiefly explained by the fact that nonwoven filter fabrics are much thicker than filter papers (g = 2.4–3.9 mm as against g = 0.6–0.9 mm, respectively).

2. The maximum values of the k_m coefficient for nonwoven fabric operating as the secondary filtration stage downstream of a uniflow cyclone are by about 50% lower than those for the nonwoven fabric operating in single-stage filtration conditions and receiving dust of standard particle size distribution (k_m = 343–290 g/m^2).

3. The use of an inertial air cleaner as the primary filtration stage results in the service life of the nonwoven filter element being extended in spite of a reduction in the maximum value of the dust absorption coefficient k_m due to the lower (by about 90 %) mass of the dust directed onto the filter element.

4. Thanks to radically (fivefold) higher maximum dust absorption coefficient of nonwoven fabrics working as the secondary filtration stage in comparison with that of filter papers

operating in identical conditions, the service life of a filter element made of nonwoven fabric (until the maximum acceptable filter restriction value of Δp_w = 5 kPa is reached) will be longer accordingly.

References

[1] BACZEWSKI, K.; HEBDA, M.: *Filtracja płynów eksploatacyjnych* (*Filtration of operating fluids*). MCNEMT, Radom, 1991/92.

[2] DURST, M.; KLEIN, G.; MOSER, N.: *Filtration in Fahrzeugen. Mann+Hummel GMBH publications,* Ludwigsburg, Germany, 2005.

[3] DZIUBAK, T.: *Analiza procesu filtracji powietrza wlotowego do silników pojazdów specjalnych* (*Analysis of the intake air filtration process in engines of special vehicles*). Post-doctoral dissertation, WAT (Military University of Technology), Warszawa, 2008.

[4] DZIUBAK, T.: *Filtracja powietrza wlotowego do silników spalinowych pojazdów mechanicznych* (*Intake air filtration in engines of special vehicles*). WAT (Military University of Technology), Warszawa, 2012.

[5] DZIUBAK, T.: *Badania eksperymentalne papieru filtracyjnego do dwustopniowego filtru powietrza silnika pojazdu specjalnego* (*Experimental research of air two-stage paper filter of special vehicle engine*). Bulletin of the Military University of Technology, Vol. 59, No. 3, 2010.

[6] DZIUBAK, T.; SZWEDKOWICZ, S.: *Badania eksperymentalne papieru filtracyjnego pracującego w systemie „cyklon – przegroda porowata*" (*Experimental research of filtration paper operating in "cyclone-porous barrier" system*). Bulletin of the Military University of Technology, Vol. 62, No. 1, 2013.

[7] DZIUBAK, T.; SZWEDKOWICZ, S.: *Badania eksperymentalne cyklonów przelotowych filtrów powietrza silników spalinowych* (*Experimental research of axial cyclones of combustion engines air filters*). Bulletin of the Military University of Technology, Vol. 62, No. 2, 2013.

[8] DZIUBAK, T.; SZWEDKOWICZ, S.: *Badania eksperymentalne włókniny do filtracji powietrza wlotowego silników spalinowych pojazdów mechanicznych* (*Experimental research of intake air filtering fibers in motor vehicle engines*). Combustion Engines – Silniki Spalinowe, Vol. 155, No. 4, 2013, pp. 33–43.

[9] FLECK, S.; HEIM, M.; BECK A.; MOSER, N.; DURST, M.: *Realitätsnahe Prüfung von Motoransaugluftfiltern*. MTZ 05/2009 Jahrgang 70.

[10] GRAFE, T. H.; GRAHAM, K. M.: *Nanofiber Webs from Electrospinning.* Proceedings of the "Nonwovens in Filtration" 5th International Conference, Stuttgart, Germany, March 2003.

[11] GRAFE, T.; GOGINS, M.; BARRIS, M.; SCHAEFER, J.; CANEPA, R.: *Nanofibers in Filtration Applications in Transportation.* Proceedings of the "Filtration 2001" International Conference and Exposition, Chicago, Illinois, December 3–5, 2001.

[12] GRAHAM, K.; OUYANG, M.; RAETHER, T.; GRAFE, T.; MC DONALD, B.; KNAUF, P.: *Polymeric Nanofibers in Air Filtration Applications.* 5th Annual Technical Conference & Expo of the American Filtration & Separations Society, Galveston, Texas, April 9-12, 2002.

[13] Korea Filtration Technologies Co.: *Performance mill sheet.* Company's materials, by courtesy of WIX Filtron, Gostyń.

[14] KOSMIDER, K.; SCOTT, J.: *Polymeric Nanofibres Exhibit an Enhanced Air Filtration Performance.* Filtration & Separation, Vol. 39, No. 6, 2002.

[15] NORTON, T.: *Hybrid membrane technology: A new nanofibre media platform.* Filtration & Separation, Vol. 44, No. 2, 2007.

[16] PN-S-34040. *Filtry powietrza. Wymagania i badania* (*Air filters. Requirements and tests*). PKN, 1996.

[17] *PowerCore™, Innovative Air Filter Technology.* www.donaldson.com.

[18] *Power Core G2 and Ultra-Web® Filtration Technology*. www.donaldson.com.

[19] SANDERS, R.; BÜHLER, A.; DURST, M.; MOSER, N.; PELZ, A.: *Effiziente Motorluftfiltration durch den Einsatz von Nanofasern*. MTZ 68, No. 2, 2007.

[20] SCHLOSS, M.: *Upgrading indoor air filtration: The right decision, the right time*. Filtration & Separation, Vol. 44, No. 1, 2007.

[21] SZWEDKOWICZ, S.: *Projekt wstępny metodyki badań chłonności pyłowej materiałów filtracyjnych filtrów powietrza pojazdów mechanicznych* (*Preliminary design of a method of testing the dust-holding capacity of motor vehicle air cleaners*). Master's graduation work, supervised by T. Dziubak, WAT (Military University of Technology), Warszawa, 2010.

[22] TRAUB, M.: *Mahle Symmetrix Hohe Filterleistung auf kleinem Bauraum*, MTZ 68, No. 2, 2007.