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EXPERIMENTAL RESEARCH OF THE MATERIAL FILTRATION CHARACTERISTICS WITH NANOFIBERS ADDITION

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Abstract

Nanofiber properties and the possibilities of their application in industry, including car air intake filtration materials production for vehicle engines are discussed. The attention is paid to the standard filtration materials low efficiency in the range of dust grains below 5 μm. Filtration materials properties with nanofibers addition are presented. Filter paper test conditions and methodology at the station with particle counter were developed. Filtration efficiency characteristics, and accuracy studies as well as filtration materials pressure drop differing in structure were made: standard paper, and materials with nanofibers addition. These are commonly used filter materials for car air intake systems production. Filtration materials with nanofibers addition test results show significantly higher efficiency values, and efficiency for dust grains below 5 μm in comparison with standard filter paper. It was found that there are 16 μm dust grains in the airflow behind the cellulose insert, which may be the reason for the accelerated wear of the engine's "piston-cylinder" association. Lower dust mass loading k_m values of filtration materials with nanofibers addition in relation to standard filter papers were observed.

Keywords: *engine, air filter, filtration materials, nanofiber filter media, filtration efficiency, filtration performance, pressure drop, dust mass loading*

1. Introduction

The dominant filter material of modern inlet air internal combustion engines is filter paper (porous material), characterized by filtration performance $d_z \geq 5$ μm, filtration efficiency at $\varphi_w = 99.9\%$, low thickness $g_m = 0.4\text{-}0.8$ mm, and the same small ($k_m = 200\text{-}250$ g/m^2) dust absorptivity limited by the permissible pressure drop Δp_{fdop} of the air filter [2, 4-7]. Filter papers stop dust grains on the fibres (which have approx. diameter of 20 μm) of the porous barrier due to the various forces, and filtration mechanisms. Over time, dust grains are deeply embedded in the fibrous structure of the filtration media, preventing the proper airflow. As a result, there is a continuous pressure drop on the filter, until the value of Δp_{fdop} is reached, which is the criterion of air filter usage end, and the exchange of the filter cartridge.

It is believed that all dust grains above $d_z \geq 1$ μm cause accelerated wear of internal combustion engine components [1-4, 8]. The only way to protect motors against excessive wear of friction surfaces is to use materials with high efficiency, and filtration accuracy. Such possibilities are created by polymer nanofibers, i.e. fibres with a diameter of less than 1 μm. A thin layer of nanofibers applied from the inlet side to a standard filter bed (e.g. cellulose) retains particles of impurities, before they penetrate into the filter material. The development of fibre production technology has caused that more and more often, filter manufacturers, for example: Donaldson, Maan-Hummel, use filtration materials with an additional nanofiber layer. The dust particles retention on the surface of the layer of nanofibers allows their subsequent removal (filter cleaning) by means of reverse (in the opposite direction to the direction of airflow during operation) of a compressed air pulse under high pressure. If the dust particles are on the filter material surface, they do not damage (break) the structure of the filter cartridge when they are blown out.

In the available literature, the data characterizing the properties of filtration materials with the addition of nanofibers is not very common. Hence, it is advisable to carry out experimental investigations of filtration materials with the addition of nanofibers in terms of efficiency, filtration performance, and pressure drop. Such studies are expensive and labour-intense; however, this is the most reliable research method.

2. Nanofibers filtration materials properties

Nanofibers have completely different properties compared to standard fibres. First of all, in relation to the mass, they have a large surface area, much higher strength, and they are also characterized by higher chemical activity, and higher moisture sorption. They can be used to build filters to separate chemical or biological contaminants from the blood plasma; they can be used as gas filters, and impurities with very small diameters – filters with molecular separation. Due to their structure, nanofibers materials have unique properties, and offer unexpected possibilities of their application in many fields, such as in medicine, energy and air filtration [15].

Nanofibers can be made from different polymers, and thus have different physical properties. Examples of natural polymers include collagen, cellulose, silk fibroin, keratin, gelatine, and polysaccharides, such as chitosan and alginate. Nanofibers diameter depends on the type of used polymer, and the method of production [16]. All polymer nanofibers are unique due to their large area, and volume, considerable mechanical strength, and small fibre diameter. Filter media made of nanofibers are characterized by high porosity and small pore sizes [9, 11-13]. Fig. 1 shows a human hair and plant pollen on the background of a bed of nanofibers [19].

a) b)

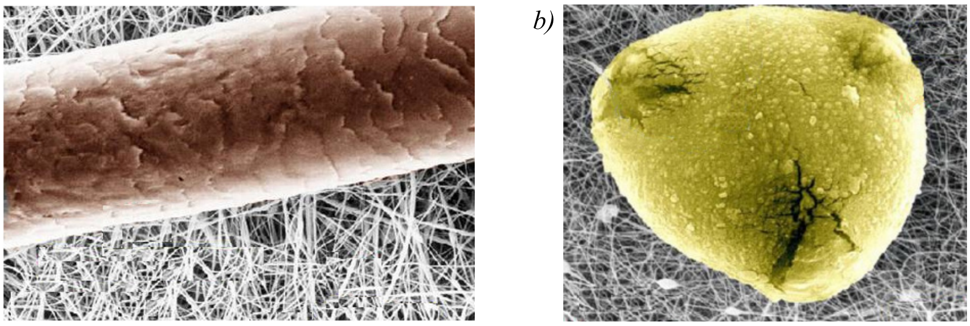

Fig. 1. Comparison against the background of nanofibers bed: a) human hair, b) plant pollen [19]

The most widely used method of producing nanofibers is the electrospinning method [16]. It is a process of obtaining fibres from molten polymers or their solutions, using high voltage. This modern technology, using the right polymer, and dissolution system, now allows the production of fibres with diameters ranging from 3 nm to 1000 nm. Virtually any polymer can be obtained in the form of fibres by electrospinning. Nanofibers have many possible technological and commercial applications in the following areas: tissue engineering, drug delivery (release), diagnosis of carcinogenic changes, lithium-air batteries, optical sensors, and air filtration.

Due to the limited mechanical, and strength properties of the thin layer of nanofibers (1-5 μm), it is applied to the substrate (Fig. 2) from conventional filtration materials that have higher strength. The nanofibers may be laid on one or two sides of the substrate, which may be cellulose, nylon or polyester. Usage of nanofibers, as an additional layer applied to standard filter materials for air filters used in motor vehicles, significantly increases the efficiency and accuracy of filtration.

Figure 3a shows the fractional efficiency of a cellulose-based nanofiber filtration medium, on which a 0.3 mm nanofiber layer, $g_m = 0.1$ g/m^2, and fibre diameter in the range of 40-800 nm was placed [14]. The filtration efficiency of the developed medium was determined using dust with a grain size of 0-10 μm. For filtration speed $\upsilon_F = 0.03$ m/s, and dust grains in the range of

d_z = 0.2-4.5 μm, the filtration efficiency of this deposit reaches the values of φ = 64-99%, respectively. For a much higher filtration rate of υ_F = 0.2 m/s, filtration efficiency reaches a slightly lower level. These values are much higher, than those are based on cellulose, and commercial materials with the addition of nanofibers (Fig. 3a). The fractional effectiveness of filters made of commercial nanofibers is practically the same as in the case of filter cartridges made of high-quality cellulose.

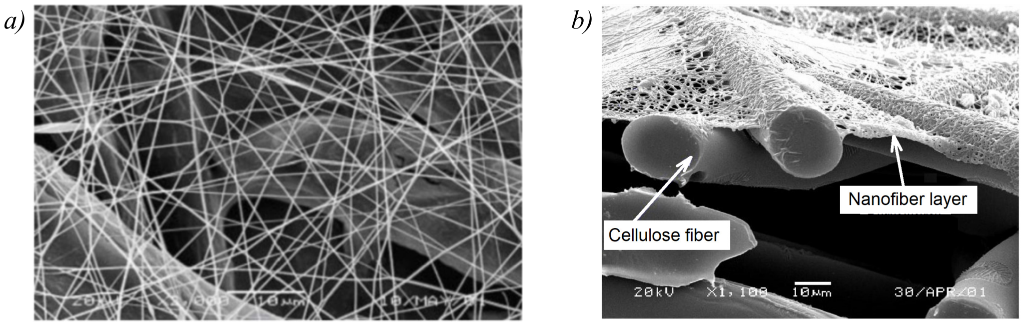

Fig. 2. Nanofibers applied to a cellulose substrate: a) top view, b) cross-section view [11]

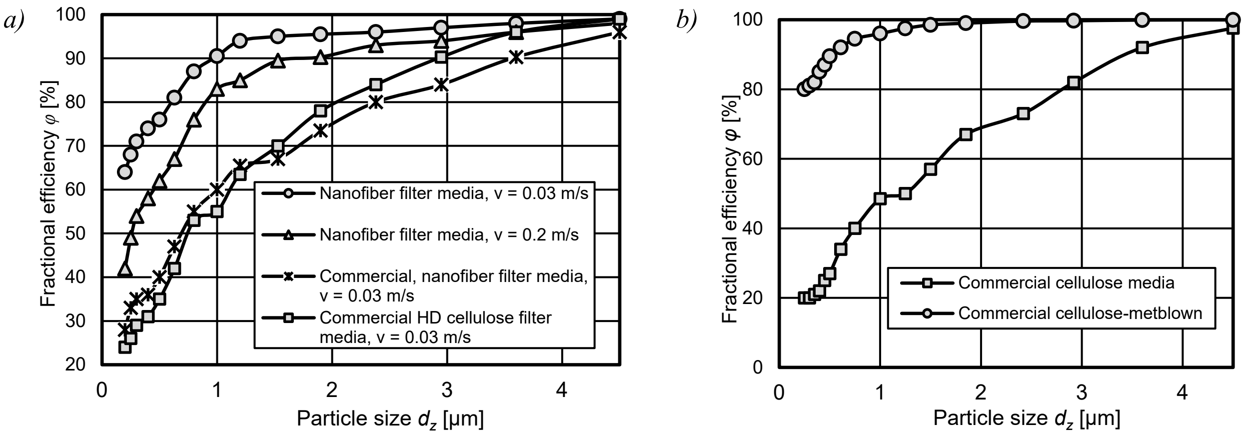

Fig. 3. a) Pleated filter elements made of cellulose fibres, nanofiber layer, and cellulose fibres filtration efficiency [14], b) air filtration effectiveness for various dust grains sizes at a flow rate of 0.03 m/s [10]

The ratio of the nanofibers to the cellulosic fibre diameter is approximately 1:130. This results in a significant increase in the filtration area for the nanofiber bed. Nanofibers area of 1 g, with a diameter of 200 nm is approximately 20 m^2/g, and only 0.2 m^2/g for cellulose fibres with a diameter of 20 μm. Fibre diameter is the main variable responsible for the filtration efficiency, and flow resistance. The efficiency increases rapidly as the fibre diameter decreases. For example, the use of fibres with a diameter of 1 μm instead of 50 μm leads to an increase in the filtration quality factor by 2000 [13, 14].

The above data shown in Fig. 3b confirms test results for two filtration cartridges: a standard one made of cellulose fibre, and a cellulose-based insert with a layer of meltblown nanofibers [10].

With the increase of the dust grain size, the efficiency of filtration for both filter cartridges gets higher and higher values, but the filtration efficiency of the filter cartridge with the nanofibers layer has higher level. For dust grains with d_z = 0.25 μm dimensions, filter cartridge filtration efficiency, with the “meltblown” nanofiber layer applied is φ = 80%, and for a standard cellulose fibre filter only φ = 20%. With the dust grain size, the difference in the filtration efficiency of both cartridges decreases and for d_z = 4.5 μm it is 99.8% and 97% respectively. Nanofibers layer usage on a standard filtration substrate also causes an increase in the pressure drop Δp. For the speed υ_F = 0.3 m/s, the insert with the addition of nanofibers has a 75% higher flow resistance Δp than the standard [10].

Standard cellulose materials have a basis weight of approx. $g_m = 250$ g/m^2. The initial material effectiveness φ_0 with nanofibers layer addition with a basis weight not exceeding $g_m = 0.1$ g/m^2, increases by 50%, with a slight increase in pressure drop Δp (Fig. 4) [11]. There is a six-time increase in the filtration quality factor q determined by the formula [9]:

$$q = \frac{-\ln(1-\varphi_0)}{\Delta p}[\text{kPa}^{-1}], \tag{1}$$

where:
φ_0 – filter bed initial efficiency,
Δp – pressure drop for the nominal air stream [kPa].

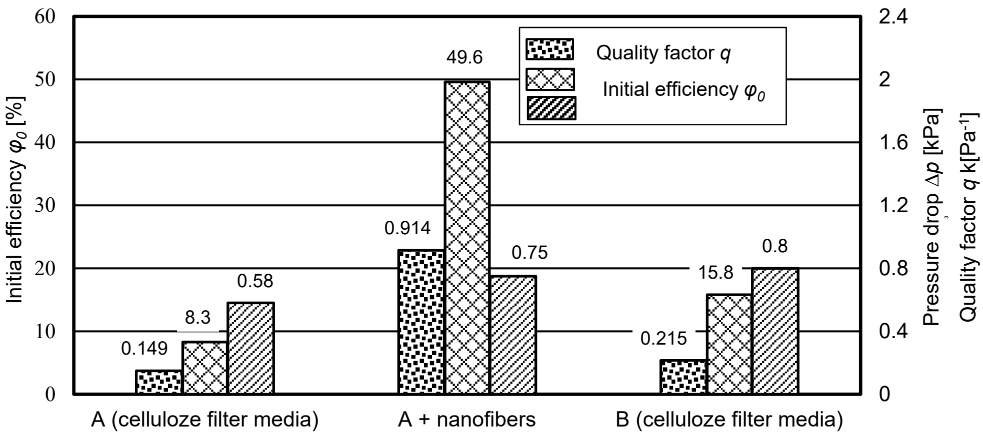

Fig. 4. Standard filtration materials effectiveness used in car air filters, and standard filtration material with a thin layer of electrospinning fibres [9]

Filtration efficiency, filtration performance and pressure drop of filtration materials with an additional nanofiber layer depends on the substrate structure (type of material), and the layer of nanofibers thickness. The paper [12] presents the results of filtration effectiveness tests of four samples made of different filtration materials: A – nonwoven, B – knitted, C – woven, D – charmeuse (silk nonwoven).

Filtration efficiency and pressure drop were determined for samples with nanofiber layers with a basis weight of: $g_m = 0.02$ g/m^2, $g_m = 0.1$ g/m^2, $g_m = 0.5$ g/m^2, and without a layer of nanofibers. Photos from the SEM microscope for sample C with a layer of nanofibers with set weights are shown in Fig. 5.

a) b) c)

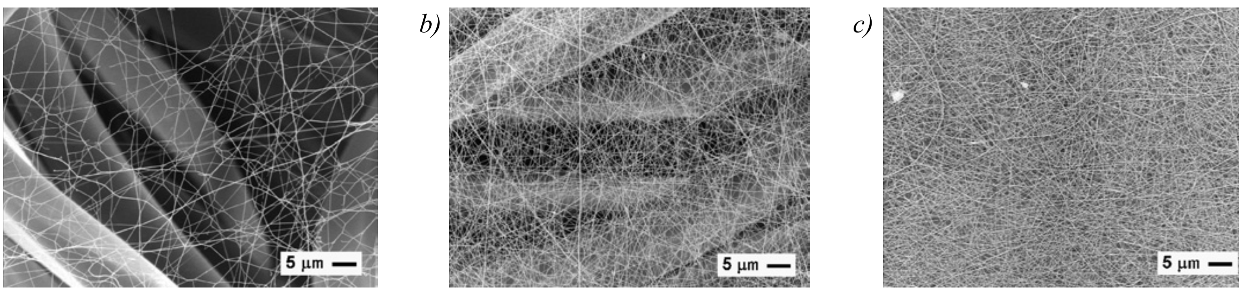

Fig. 5. SEM microscope photographs for sample C with nanofiber a basis weight layer: a) $g_m = 0.02$ g/m^2, b) $g_m = 0.1$ g/m^2, c) $g_m = 0.5$ g/m^2 [12]

The nanofibers had an average diameter of 140 nm with a standard deviation of 30 nm. The average pore size for the nanofiber layer with the basis weight $g_m = 0.02$ g/m^2, $g_m = 0.1$ g/m^2, $g_m = 0.5$ g/m^2 were respectively 1190 nm, 540 nm and 260 nm.

layer is very low, and for particle sizes below 2 μm does not exceed 10%. A small layer of nanofibers with $g_m = 0.02$ g/m^2 increases the filtration efficiency of particles smaller than 2 μm over 60%. Nanofibers layer with $g_m = 0.1$ g/m^2 increased the filtration efficiency of particles with dimensions of 2 μm to the value of about 90%, and for $g_m = 0.5$ g/m^2 – to the value of over 99%.

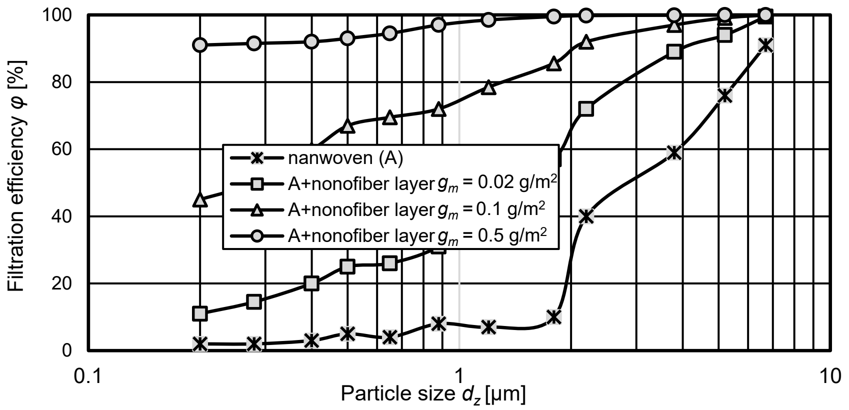

Fig. 6. Material filtration effectiveness (nonwoven fabric sample A) without a nanofiber layer, and with nanofiber layer with unit weight $g_m = 0.02$ g/m^2, $g_m = 0.1$ g/m^2, $g_m = 0.5$ g/m^2 [12]

There are known constructional solutions for vehicle inlet air filters (Abrams M1 tank), where a filter cartridge with the addition of nanofibers, and a system of automatic impulse purification of the PJCA (Pulse Jet Air Cleaner) filter cartridge is used [10]. It ensures several times longer air filter life, and thus longer vehicle life without the need to operate the filter. The principle of PJAC operation system is that at the time when the pressure drop of the filter inflow does not exceed the permissible value, the air filtration process takes place, as in every vehicle filter. After pressure drop reaches certain value, a pressure modulator is activated for 0.1-0.35 s, producing a pulse in the form of compressed air with a pressure of 0.4-0.6 MPa. Compressed air flowing in the opposite direction, to the airflow direction during the filtration process, blows out dust particles from the surface of the filter cartridge, which then falls into the dust collector [17].

Figure 7 shows that the standard filter cartridge, mounted in a tank which moves in the column in desert conditions, reaches the permissible value of pressure drop, $\Delta p_{fdop} = 7.6$ kPa (30 inches of H_2O) after driving about 25 km (16 miles).

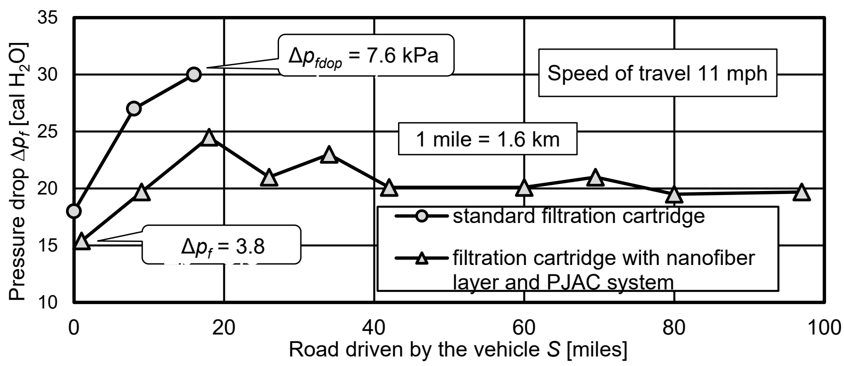

Fig. 7. Air cleaner pressure drop versus miles travelled in 20 mph convoy test in desert conditions and automatic cleaning system [10]

When a filter cartridge with a nanofiber layer equipped with an automatic pulse cleaning system reaches maximum pressure drop of approximately 6.3 kPa (25 inches of H_2O), the pulse cleaning system will be activated. After removing the dust from the nanofiber layer, the pressure drop decreases to approximately 5 kPa (20 inches of H_2O), and remains at this level.

3. Aim, scope and research subject

The aim of the research was to determine, and compare filtration properties: efficiency and accuracy of filtration, and filter cartridges flow resistance made of various filter materials (cellulose, polyester with the addition of nanofibers) by determining their following characteristics:
- filtration performance $d_{zmax} = f(k_m)$,
- filtration efficiency $\varphi_w = f(k_m)$,
- pressure drop $\Delta p_w = f(k_m)$,

where: k_m – dust mass loading, determining dust mass m_w retained, and evenly distributed over 1 m^2 of filter material active surface, which is expressed by the dependence:

$$k_m = \frac{m_w}{A_w} \text{ [g/m}^2\text{]}. \tag{2}$$

The filtration speed is defined as the quotient of the air stream flowing through the filter cartridge Q_w (equal to the engine air demand). The area of the active paper filters A_w is expressed by the following relationship:

$$v_{Fw} = \frac{Q_w}{A_w \times 3600} \text{ [m/s]}. \tag{3}$$

The subject of the research were four filter cartridges of the same type, same dimensions, same filtration surface $A_w = 0.153$ m^2, but differing in the filter material. On two standard filtration materials, there is a nanofiber layer on the inlet side. In order, make test analysis easier, filter materials have been labelled as follows:
- A (cellulose),
- B (polyester),
- C (polyester + nanofiber layer),
- D (cellulose + polyester + nanofiber layer).

Tested filter materials characteristic parameters are summarized in Tab. 1. Three times higher air permeability, and double the size of the filter material A (cellulose) pores from other materials is noteworthy.

Tab. 1. Tested filtration materials parameters according to the manufacturer's data

Filter paper identification	Filtration material	Permeability q_p [m^3/m^2/h], 200 [Pa]	Grammage g_m [g/m^2]	Thickness g_z [µm]	Pore size d_p [µm]	Grammage $q = g_m/g_z$ [g/m^2/µm]
A	Cellulose	3017	121	610	79	0.198
B	Polyester	650	180	500	–	0.36
C	Polyester + nanofibers	525	180	500	–	0.36
D	Cellulose + polyester + nanofibers	660	120	300	48	0.4

4. Method and test conditions

Tests were carried out at the station (Fig. 8), which was equipped with the Pamas-2132 particle counter with the HCB-LD-2A-2000-1 sensor. The meter registers the number and size of dust grains in the air stream Q, behind the tested filter cartridge in the range of 0.7-100 µm in $i = 32$ measurement intervals, limited by diameters (d_{zimin}-d_{zimax}).

At the appropriate distance after tested filter, the tip of the measuring probe is placed centrally in the axis of the cable, which is followed by air suction to the particle counter sensor. The measuring lead ends with a special (absolute) filter, which prevents dust from entering the rotameter, and at the same time, it is a measuring filter. The cover in which the cylindrical filter cartridge is located, PTC-D test dust is being dispensed as the national replacement for AC fine test dust, whose chemical, and fractional composition is given in [18].

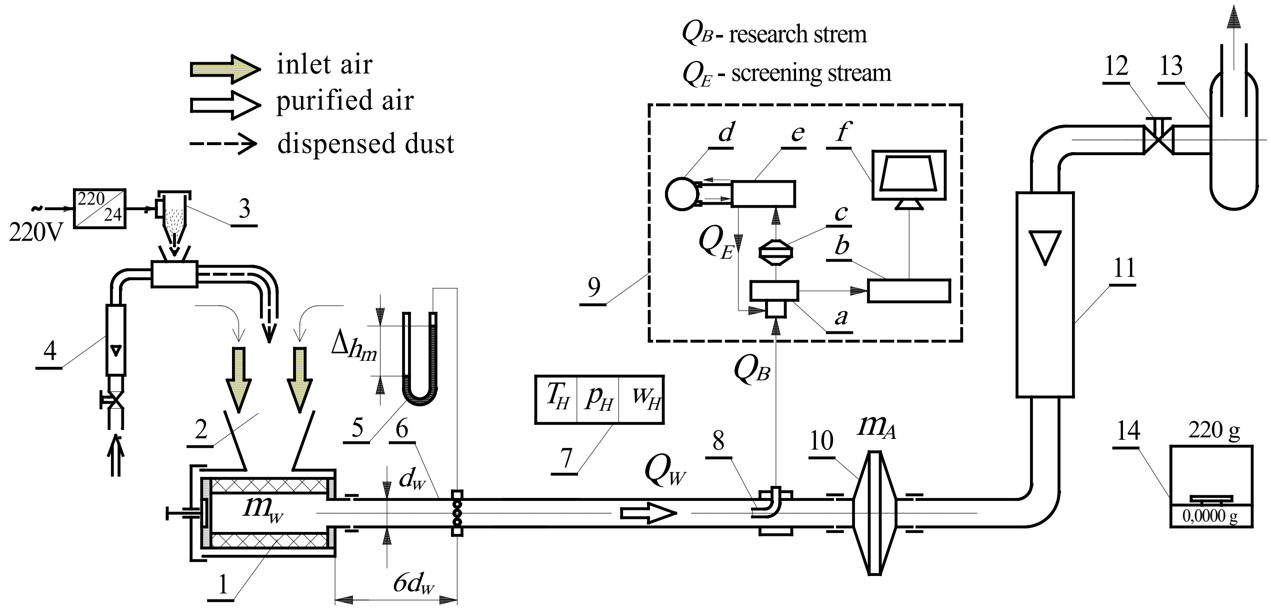

Fig. 8. Filter cartridge test stand functional diagram: 1 – filter cartridge, 2 – dust chamber, 3 – dust dispenser, 4 – rotameter, 5 – U-type manometer tube, 6 – measuring tube, 7 – humidity measurement set , ambient air temperature and pressure, 8 – measuring probe, 9 – particle counter (a – sensor, b - counter microprocessor, c – test stream filter, d – vacuum pump, e – flow control block, f – measuring computer), 10 – absolute filter, 11 – rotameter, 12 – air stream regulation valve, 13 – suction fan, 14 – analytical balance

The pressure drop Δp_w in the cartridge was defined as the decrease of the static pressure in the outlet pipe at a distance of $6d_w$ from the edge of the cartridge outlet on the basis of the Δh_j [mm H_2O] indicator on the U-tube liquid manometer, according to the relationship:

$$\Delta p_j = \frac{\Delta h_j}{1000} \cdot 9.807 \text{ [kPa]}. \quad (4)$$

Cartridges filtration characteristics were determined for the filtration speed $\upsilon_{Fw} = 0.1$ m/s. For passenger car filters, the maximum speed of paper filtration is in the range of 0.07-0.12 m/s [2, 3, 6, 7, 19]. For the assumed filtration rate ($\upsilon_{Fw} = 0.1$ m/s), *the* maximum value of the test stream calculated according to the following relationship has the value $Q_{wmax} = 56$ m^3/h.

$$Q_{wmax} = A_w \cdot v_{Fw} \cdot 3600 \text{ [m}^3\text{/h]}, \quad (5)$$

where: tested inserts filtration surface $A_w = 0.153$ m^2.

The RIN 60 rotameter of the measuring range 3-67 m^3/h and the accuracy class 2.5 was assumed for air stream measurement.

Tested filtration materials filtration characteristics were determined by the gravimetric method. Dust mass retained on the tested filter cartridge, and the absolute filter was determined in subsequent measuring cycles with a specified duration. The concentration of dust in the inlet air to the filter cartridge $s = 0.5$ g/m^3 was used. The tests were carried out in measuring cycles j with duration (time of equal dust dosing) $\tau_p = 3$ min in the initial period, and $\tau_p = 9$-12 min in the basic period of filter cartridges work. After each measuring cycle j, the parameters necessary to calculate: efficiency, filtration performance, pressure drop and dust mass loading of the filter cartridge were determined. The dust mass was determined by an analytical balance with a measuring range of 220 g and an accuracy of 0.1 mg.

Cartridge filtration efficiency was determined based on the measured dust mass values according to the following relationship:

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

where:

m_{Zj} – dust mass stopped in time τ_{pom} , on the filter cartridge of the next j measuring cycle,

m_{Aj} – dust mass stopped by the absolute filter during τ_{pom} time of the next measuring cycle j.

The cyclone filtration performance was defined as the largest grain size of $d_z = d_{zmax}$ located in a given air stream test cycle behind the filter cartridge.

Mass loading of dust k_{mj} value was determined from of the formula:

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

5. Test results analysis

Test results filtration efficiency φ_f, filtration performance d_{zmax}, and pressure drop Δp_f calculations of tested filtration materials are shown in Fig. 9. As the dust, mass retained in the filtration layer increases (k_m coefficient increase) the filtration efficiency, filtration performance and pressure drop of filter cartridges assume increasing values. This is the result of the space filling between the fibres (pores), which are consistent with the literature [3, 4, 6, 13, 14].

The work of tested filter cartridges can be divided into two stages. It was assumed that the first (I), the initial stage of filter cartridges operation, lasts until the filtration efficiency stabilizes at the level of $\varphi_w = 99.9\%$. This stage is characterized by low initial efficiency, filtration performance, and low-pressure drop.

For a filter cartridge made of filter material A (cellulose), the initial filtration efficiency is $\varphi_{wA} = 96.5\%$, and the maximum grain size does not exceed the value of $d_{zmaxA} = 16.7$ µm. The determined value of filtration efficiency ($\varphi_w = 99.9\%$) is achieved at the dust mass loading $k_{mA} = 91$ g/m^2, while the pressure drop increase is insignificant. For the other cartridges made of other filtration materials, the first stage is much shorter. For the B (polyester) insert, stage I ends with the dust mass loading $k_{mB} = 70.6$ g/m^2, for the cartridge C (cellulose + polyester + nanofibers) $k_{mC} = 25.2$ g/m^2, and for the contribution D (polyester + nanofibers) coefficient $k_{mD} = 8.23$ g/m^2. The initial filtration efficiency for the mentioned cartridges is assumed to be higher, respectively: $\varphi_{wB} = 98.4\%$, $\varphi_{wC} = 99.3\%$, $\varphi_{wD} = 99.6\%$. At the end of the first stage filtration, the sizes of the maximum grains for the contributions A, B, C, D are stabilized at the following level: $d_{zmaxA} = 4.7$ µm, $d_{zmaxB} = 3.9$ µm, $d_{zmaxC} = 3.1$ µm, $d_{zmaxD} = 3.5$ µm. The initial work stage of the A cartridge made of cellulose is several times longer than the insert D (polyester with a layer of nanofibers) and the contribution of C (cellulose + polyester + nanofibers). At the same time, the required high filtration efficiency of the inserts with nanofiber layer reach much earlier than cartridges made of standard filter material. This confirms the literature information about the positive nanofibers influence on the filtration efficiency, and filtration performance materials used in automotive industry.

In the first filtration stage, the dirt particles deposit on the fibres surface of the porous structure, and on previously deposited particles. In this way, they form slowly growing complicated dendritic structures (agglomerates) that fill free spaces between fibres. They affect the flow field around the fibres. In response to changes in the filter structure, there are changes in the airflow. This has the effect of increasing the flow resistance through the filter bed.

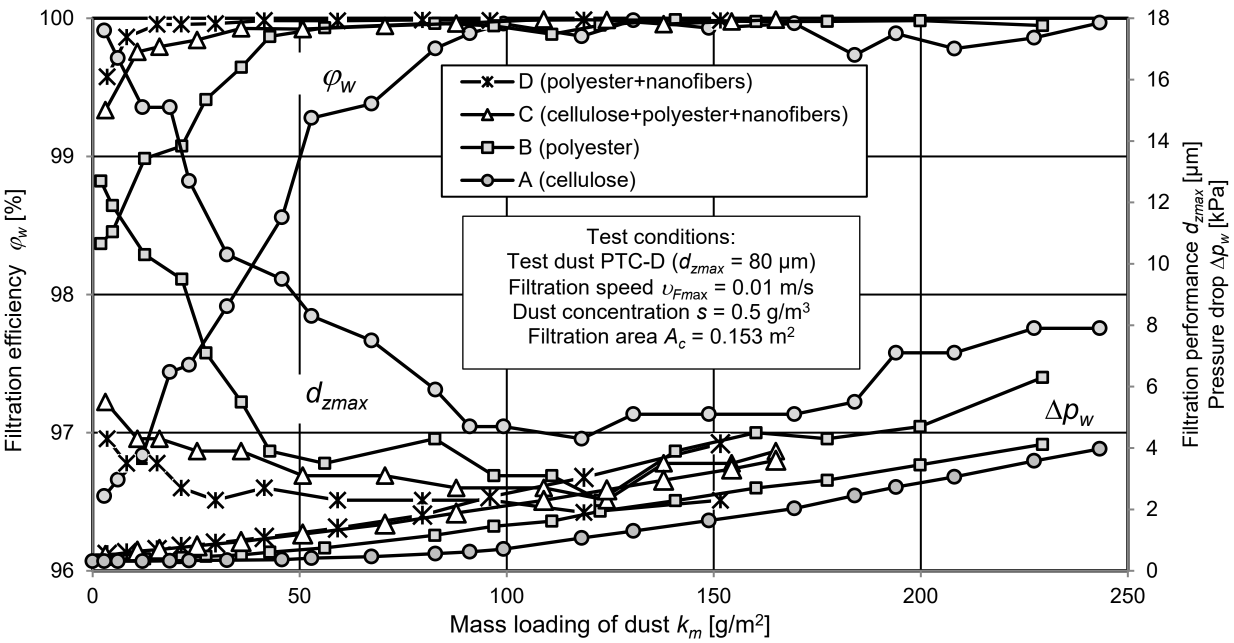

Fig. 9. Filtration efficiency φ_w, filtration performance, d_{zmax}, and pressure drop Δp_w depending on the tested filter cartridges dust mass loading k_m

In the second (II) stage of the filtration cartridges, the filtration efficiency remains unchanged, stabilized $\varphi_W = 99.9\%$. In contrast, the pressure drop reaches higher and higher values, but the intensity of growth is greater for inserts made of materials with nanofibers addition. Filter cartridge D achieves pressure drop $\Delta p_{maxD} = 4.1$ kPa with dust mass loading of $k_{mD} = 151.6$ g/m^2. Filter cartridge A similar pressure drop value ($\Delta p_{maxA} = 3.96$ kPa) achieves at the dust mass loading $k_{mA} = 243$ g/m^2. Inserts with nanofiber layer are characterized by lower dust absorption. This is determined by the surface filtration, as a result of which the dust grains are not allowed into the deposit, but are mostly retained on the nanofiber layer. This is illustrated by the measurement results (Fig. 10) of the maximum dust grains size d_{zmax} in the air after the tested cartridges. In the air after the insert A (cellulose) there are grains with the dimensions of $d_{zmaxA} = 4.3$-16.7 µm, and behind the insert D, where there is nanofiber layer, grains with much smaller dimensions $d_{zmaxD} = 2.3$-4.3 µm.

Filter elements made of cellulose composite and polyester, together with the applied layer of nanofibers, are characterized by higher efficiency, and filtration performance in the whole range of work (smaller dust grain sizes d_{zmax} in the air behind the filter cartridge) than inserts made of filter material without a layer of nanofibers.

Filter inserts with a nanofiber layer obtain a maximum mass loading of dust of $k_m = 150$-165 g/m^2. For a similar pressure drop value Δp_{wdop} (about 4 kPa) filter cartridges without nanofibers layer obtain dust mass loading in the range of $k_m = 230$-243 g/m^2, which is 50% more value. This is due to the lower pressure drop intensity of the filter cartridges without the nanofibers layer. After the filtration inserts with nanofiber layer have a pressure drop of 4 kPa, the phenomenon of dust agglomeration from the filter bed is observed. This is a proof that in filter beds with nanofiber layer, mainly surface filtration occurs, not deep.

Low efficiency, and filtration performance in the initial period of filter cartridges work without nanofibers layer (this is the case after replacing a contaminated filter cartridge with a new one) causes that dust particles larger than 5 µm in the air entering the engine can have a significant impact on accelerated wear of engine components, mainly cylinder funnel – piston ring-cylinder, association. Such phenomenon is not observed, when using filter cartridges with a layer of nanofibers.

In the final stage of filtration, large dust grains ($d_{zmaxA} = 7.9$ µm) are found in the air behind the filter cartridge A. There is also a noticeable decrease in cartridge filtration (Fig. 9). This indicates that the grains have passed to the outlet side of the filter material. In the final stage, a significant dust mass is accumulated in the form of expanded tree-like dendrites. The dust grains located at the very top of the dendrites are entrained and transferred to the outlet side of the filter material. As a result of this phenomenon, along with the inlet air, dust flows into the engine cylinders.

Measurements results of dust grains numbers in the air after the tested filter cartridge (passed through the filter material) are shown in Fig. 10 and 11.

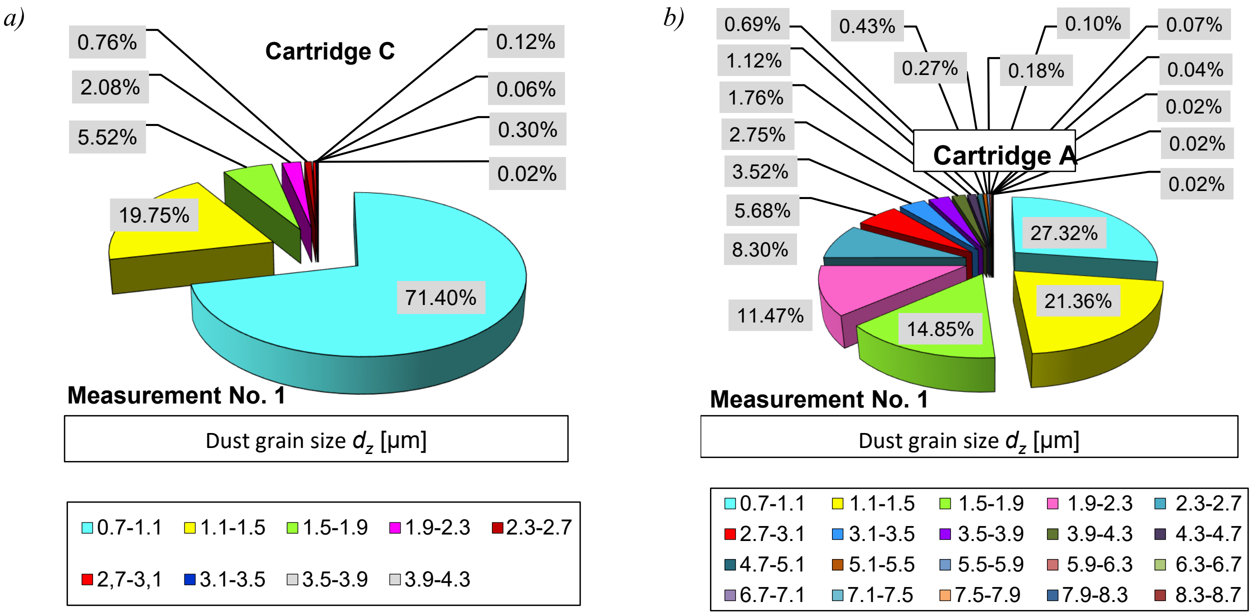

Fig. 10. Granular composition of dust grains assumed by the filter cartridge: a) cartridge C (cellulose+ polyester nanofibers) after reaching dust mass loading k_m = 3 g/m^2, b) cartridge A (cellulose) after reaching the dust mass loading k_m = 2.8 g/m^2

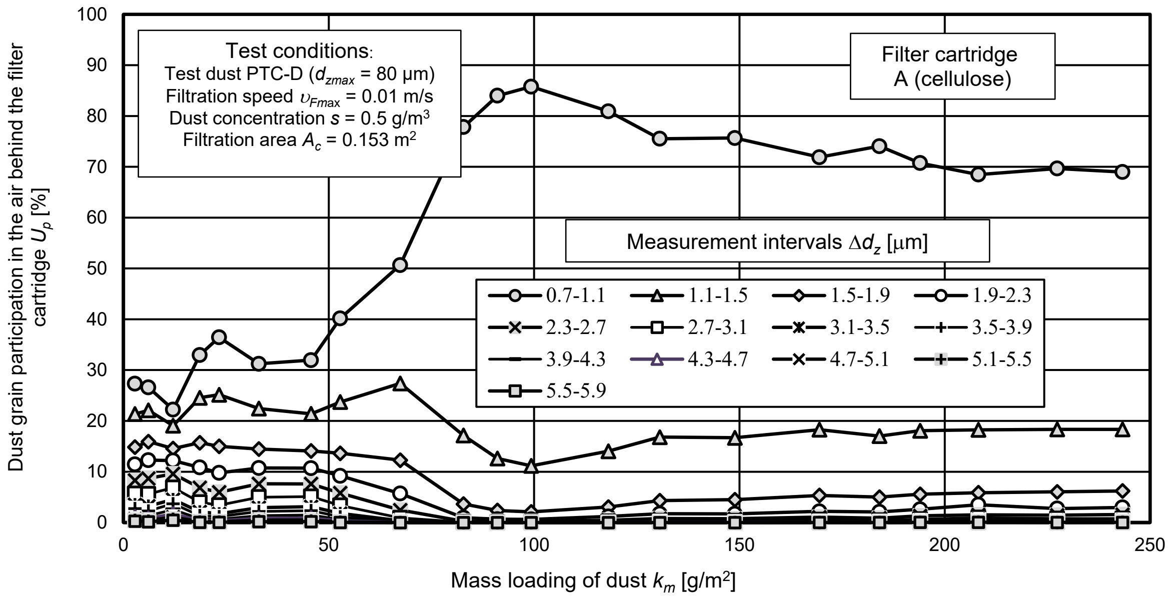

Fig. 11. Dust grains granulometric composition, which passed through filter cartridge A (cellulose)

The largest part in the air is dust grain, which have dimensions of 0.7-1.1 μm. For filter cartridge C, this is a constant value, slightly over 70%. For the first measurement, the part of dust grains in the range of 0.7-1.1 μm is U_{z1} = 71%, for the measurement number 3 – U_{z3} = 73%, and for the measurement number 8 – U_{z8} = 72%. For the remaining measuring compartments, the part of dust grains in the air with each measurement decreases, which indicates the increasing filtration efficiency of the tested material. After the filter achieved the maximum efficiency of φ_{max} = 99.99%, there were dust particles smaller than 2.7 µm in purified air.

Part of dust grains of 0.7-1.1 µm for the filter cartridge A (cellulose) is much smaller than the contribution of C (27% at the time of the first measurement) and increases to 85%, and then decreases to about 70% (Fig. 11). The share of dust grains of 1.1-1.5 µm size is in the range of 20-27% until reaching the dust mass loading k_m = 67 g/m^2, and then decreases to about 18%, after which it remains at a constant level. For the next measurement intervals, including dust grains above 1.5 µm, the shares of dust grains are getting smaller (Fig. 11), and their changes depending on the k_m coefficient are similar to the shares of dust grains from 1.1 to 1.5 µm range. In the air behind the filter cartridge A (made of cellulose) after reaching the maximum filtration efficiency φ_{maxA} = 99.96% there were dust grains with dimensions below 4.7 µm.

6. Conclusions

1) Nanofiber layer with a thickness of few micrometres applied on a substrate made of conventional filter materials for car air filters increase the filtration efficiency and filtration performance, especially for dust grains below 5 µm, without a significant pressure drop.
2) Filtration materials with the addition of nanofibers create, upon reaching a certain pressure drop value, the possibility (Abrams M1 tank) of the filter cartridge impulse cleaning, by compressed air stream, which ensures few times longer air filter life.
3) The available literature data has a limited amount of information when it comes to filtration filter inserts properties with nanofiber layer, and all the values of filtration efficiency, and accuracy, hence it is advisable to carry out experimental research.
4) With the increase of dust mass retained on the filter cartridge (increase in the dust mass loading k_m of the cartridge), the filtering efficiency of the tested cartridges increases dramatically during the initial period, however a more intense increase is observed for the insert with the nanofiber addition. The filter insert with the nanofiber layer achieves the initial filtration efficiency φ_{w0} = 99.34%. Such filtration efficiency value, cellulose cartridge reaches when the dust mass loading k_m = 53 g/m^2. The initial filtration efficiency of this cartridge is φ_{w0} = 96.54%.
5) The filtration cartridge with nanofiber addition in the whole range of work, achieves the filtration performance (maximum size of dust grains d_{zmax}) in the range of d_{z1max} = 2.7-5.5 µm. Filtration performance of the cellulose cartridge in the initial period reaches the value of d_{z1max} = 2.7-5.5 µm, and after obtaining almost 50% of the total working time of the cartridge, the accuracy is at the level of d_{z2max} = 4.7 µm. Such air with mineral dust sucked into car cylinder can accelerate its usage.
6) Filter cartridges characteristics test results; clearly show that filtration materials with nanofiber addition outweigh their properties from cartridges made of standard filtration material – cellulose.

References

[1] Barris, M. A., *Total Filtration™: The influence of filter selection on engine wear, emissions, and performance*, SAE 952557, 1995.
[2] Diesel Engine Air Filtration, *Materiały informacyjne firmy PALL Corporation*, USA, 2004.
[3] Bugli, N., *Automotive engine air cleaners – performance trends*, SAE Technical Paper 2001-01-1356.
[4] Durst, M., Klein, G. Moser, N., *Filtration in Fahrzeugen*, Mann+Hummel GMBH, Ludwigsburg, Germany 2005.

[5] Dziubak, T., *Problems of dust removal from multi-cyclones of engine air cleaners in cross-country motor vehicles*, The Archives of Automotive Engineering, Vol. 76, No. 2, pp. 37-62, 2017.
[6] 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*, Eksploatacja i Niezawodność – Maintenance and Reliability, Vol. 17, No. 4, pp. 519-527, 2015.
[7] Erdmannsdörfer, H., *Lesttingmoglichkeiten von Papierfiltern zur Reinigung der Ansaugluft von Diselmotoren*, MTZ, 32, pp. 123-131, 1971.
[8] Fitch, J., *Clean oil reduces engine fuel consumption*, Practicing Oil Analysis, 11-12, 2002.
[9] George, J., Forna, R., Cravero, T., *Air filtration with fine polymeric fibres*, 16-th Annual Technical Conference and Exposition 2003, Technical Sessions Papers, Reno-Nevada, June 17-20, 2003.
[10] Grafe, T., Gogins, M., Barris, M., Schaefer, J., Canepa, R., *Nanofibers in filtration applications in transportation*, Filtration 2001 International Conference and Exposition, Chicago, Illinois, December 3-5, 2001.
[11] Graham, K., et al., *Polymeric nanofibers in air filtration applications*, 5th Annual Technical Conference & Expo of the American Filtration & Separations Society, Galveston, Texas, April 9-12, 2002.
[12] Heikkilä, P., Sipilä, A., Peltola, M., Harlin, A., *Electrospun PA-66 coating on textile surfaces*, Institute of Fibre Materials Science, Tampere University of Technology, pp. 864-870, Tampere, Finland, 2007.
[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] Khajavi, R., Abbasipour, M., Bahador, A., *Electrospun biodegradable nanofibers scaffolds for bone tissue engineering*, Journal Appl. Polym. Sci, Vol. 133 (3), pp. 42883, 2016.
[16] Li, D., Xia, Y., *Electrospinning of nanofibers: reinventing the wheel?,* Adv. Mater., Vol. 16 (14), pp. 1150-1170, 2004.
[17] Lo, L.-M., Chen, D.-R., Pui, D. Y. H., *Experimental study of pleated fabric cartridges in a pulse-jet cleaned dust collector*, Powder Technology, Vol. 197, pp. 141-149, 2010.
[18] PN-ISO 5011, *Filtry powietrza do silników spalinowych i sprężarek*, PKNM, 1994.
[19] Taufkirch, G., Mayr, G., *Papierluftfilter für Motoren in Nutzfahrzeugen*, MTZ, 45, No. 3, pp. 95-105, 1984.
[20] http://www.cottonbangladesh.com/January2009/ElectroSpinning.htm, access 14. 12. 2017.

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