Article citation info:
Dziubak T. Problems of dust removal from multi-cyclones of engine air cleaners in cross-country motor vehicles. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2017; 76(2): 37-62, http://dx.doi.org/10.14669/AM.VOL76.ART2

PROBLEMS OF DUST REMOVAL FROM MULTI-CYCLONES OF ENGINE AIR CLEANERS IN CROSS-COUNTRY MOTOR VEHICLES

PROBLEMY USUWANIA PYŁU Z MULTICYKLONÓW FILTRÓW POWIETRZA SILNIKÓW TERENOWYCH POJAZDÓW MECHANICZNYCH

TADEUSZ DZIUBAK[1]
Military Univerysty of Technology

Summary

The organization of the process of extracting dust (by suction) from inertial intake air cleaners of internal combustion (IC) engines of motor vehicles has been discussed. The ejector configurations used in the dust removal systems have been demonstrated. Examples of contaminant extraction systems based on the ejection effect have been presented. The notion of dust suction ratio has been defined. The impact of this ratio on the filter restriction and air filtration efficiency characteristics of individual cyclones has been analysed. The impact of the dust extraction from the dust settling chamber of an inertial air cleaner (multi-cyclone) on the filtration efficiency has been explained. The impact of the dust extraction from the dust settling chamber on the unevenness of dust suction from individual cyclones of a multi-cyclone has been analysed and the reasons for the unevenness have been shown. The analysis results visualizing the impact of the unevenness of suction on the filtration efficiency of a multi-cyclone combined with a nonwoven fabric filter element have been quoted. The methods aimed at the obtaining of relatively even flow rates of the streams sucked off from individual cyclones have been analysed. It has been shown that even flow rates of the suction streams flowing out from

[1] Military University of Technology (WAT), ul. Gen. S. Kaliskiego 2, 00-908 Warszawa; e-mail: tadeusz.dziubak@wat.edu.pl

individual cyclones can be obtained by appropriately modifying the structure of the multi-cyclone's dust settling chamber.

Keywords: internal combustion engine, air contaminants, air cleaner (filter), multi-cyclone, filtration efficiency, dust removal (extraction, suction)

Streszczenie

Omówiono organizację procesu odsysania pyłu z bezwładnościowych filtrów powietrza wlotowego silników spalinowych pojazdów mechanicznych. Przedstawiono stosowane konfiguracje ejektorów w układach odsysania pyłu. Omówiono przykłady układów ejekcyjnego odsysania zanieczyszczeń. Zdefiniowano stopień odsysania pyłu. Przeanalizowano jego wpływ na charakterystykę przepływową i skuteczności filtracji powietrza pojedynczych cyklonów. Wyjaśniono zjawisko wpływu odsysania pyłu z osadnika filtru bezwładnościowego (multicyklonu) na skuteczność filtracji. Przeanalizowano wpływ odsysania pyłu z osadnika na nierównomierność odsysania z pojedynczych cyklonów multicyklonu oraz pokazano przyczyny nierównomierności. Przytoczono wyniki obrazujące wpływ nierównomierności odsysania na skuteczność filtracji multicyklonu i wkładu włókninowego. Przeanalizowano metody prowadzące do uzyskania względnej równomierności strumieni odsysanych z pojedynczych cyklonów. Wykazano, że równomierne wartości strumieni odsysania z pojedynczych cyklonów można uzyskać poprzez odpowiednią zmianę struktury osadnika pyłu multicyklonu.

Słowa kluczowe: silnik spalinowy, zanieczyszczenia powietrza, filtr powietrza, multicyklon, skuteczność filtracji, usuwanie (odsysanie) pyłu

1. Introduction

The atmospheric air is chiefly contaminated with dust raised from the ground by wind or by motor vehicle traffic. This can be observed in particular during the operation of tracked vehicles in roadless terrain with dry and sandy ground or on dirt roads or roads with inadequately hardened surface. In such conditions, the dust concentration in the ambient air may even reach 7 g/m^3 [1, 4, 21, 27, 28, 32, 33].

The finely dispersed hard dust particles, with sharp edges, penetrating with air into engines, cause the engines, whether of the piston or turbine type, to undergo accelerated wear of their parts and component units, which results in reduced engine service life and reliability [1, 3, 9, 22, 27, 31, 33, 34]. Therefore, the dust must be effectively eliminated from the air aspirated by internal combustion (IC) engines of motor vehicles. This task is fulfilled by air filters or cleaners, which are selected to match specific engines depending on the anticipated engine operation conditions.

In engines of many cross-country motor vehicles and construction machinery operated at dust concentrations in air exceeding 1 g/m^3, the intake air is filtered by two-stage air cleaners, where inertial separation is used at the primary filtration stage. Usually, the primary separator consists of a set of a few to several ten filtration elements (cyclones or minicyclones) connected in parallel and the whole unit is referred to as a multi-cyclone. Multicyclones are used to filter the intake air in engines of tanks PT-91 and T-72, infantry fighting vehicle BMP 1, motor trucks Volvo and Scania, tracked vehicle 2S-1, and wheeled armoured vehicle KTO Rosomak; moreover, tanks Leopard 2, Abrams, Challenger, and Leclerc may be mentioned as foreign examples of vehicles with engine intake air cleaners of this type.

At present, porous paper barriers are commonly used as the secondary air filtration stage in IC engines, although "gradient" nonwoven filter fabrics, characterized by fibre packing density increasing in the airflow direction and, in consequence, by high dust-holding capacity, also find wide application. Another technology, which is becoming increasingly popular, is the use of nanofibres, obtained from the "electrospinning" or "meltblown" processes, to build filter barriers [23, 24, 26, 30, 35].

The dust separated in each of the individual cyclones of the multi-cyclone unit is gathered in a common collector (container), referred to as dust settling chamber, from which it is then removed. During the time between maintenance (for the T-72 tank, the period to travel a distance of 1 000 km), in the conditions of high dust concentration in the ambient air, the multi-cyclone is capable to separate more than 150 kg of dust from the air. It is inadvisable to keep so much dust in the dust settling chamber because of not only limited space available but also unnecessary loading of the filter structure and, above all, possible re-aspiration of the dust in result of vehicle shocks. Therefore, the dust accumulated in the settling chamber is continuously removed from there (in most cases by suction) in the multi-cyclones designed for the filtration of intake air in engines of special vehicles. The continuous extraction of dust from the multi-cyclone dust settling chamber causes a noticeable increase in the filtration efficiency of the multi-cyclone air cleaner.

The multi-cyclone consisting of a large number of cyclones and having a common dust settling chamber is usually provided with only one or two ports through which dust is sucked off from the settling chamber. Hence, the distances between the dust extraction outlets of individual cyclones from the extraction port of the settling chamber are unequal, which results in problems with the removal of dust from the outermost cyclones of the multi-cyclone unit. This causes deterioration in the performance of the cyclones involved and, in consequence, worse filtration efficiency and accuracy (rating) of the multi-cyclone unit as a whole. Thus, the mass of the dust passed to the secondary filtration stage (paper filter element) increases, which reduces the filter life (distance travelled by the vehicle), due to limited dust-holding capacity of the filter paper, until the filter restriction limit Δp_{fdop} determined by the maximum acceptable drop (by 3 %) in the engine power output is reached. For the engines of motor trucks and special vehicles, the filter restriction limit value is set within a range of Δp_{fdop} = 5-7 kPa [1, 13, 15, 18, 28, 33].

For a high filtration efficiency of the multi-cyclone unit to be obtained, not only the design and airflow parameters of the unit should be correctly selected but also much attention should be devoted to the organization of the process of extracting the contaminants trapped in the unit.

2. Organization of the process of extracting dust from inertial air cleaners

The dust separated from the intake air is extracted from the settling chamber by a suction system, which includes dust settling chamber (separation chamber) of the multi-cyclone unit, airflow-inducing system (causing the suction effect), and tubing to carry away the dust sucked off to the outside. The suction takes place thanks to an appropriate vacuum being generated by the sucking stream, which is a part of the air stream entering the multi-cyclone (cyclone), see Fig. 1. The suction stream flows through the dust settling chamber with sweeping away dust particles and then it is directed outside the vehicle to a place so distant from the air intake that any risk of re-aspiration of the dust having been separated is avoided.

The obtaining of the extraction effect is a relatively difficult technical problem. Usually, the suction effect is generated by special fans or blowers. The mechanical sucking devices of this kind must by appropriately driven. A mechanical driving system operated by the vehicle engine is rather impracticable, e.g. due to the fact that fan performance curves strongly depend on the fan speed, i.e. on the current engine operation range. Moreover, the fan would have to be situated close to the engine, at a place that would not necessarily be appropriate for the filter location and position.

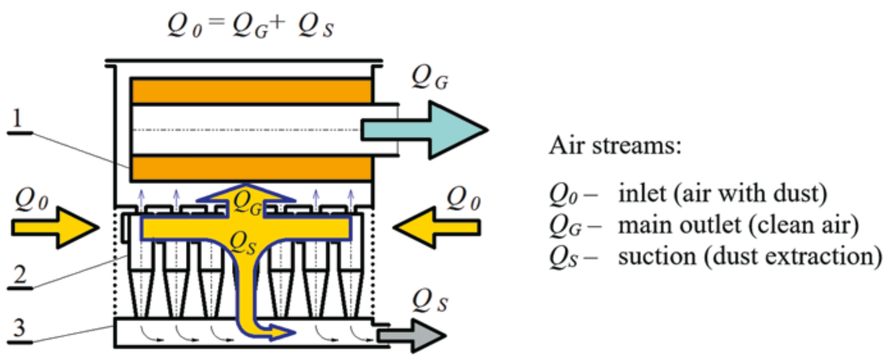

Fig. 1. Distribution of the inlet air stream in a filter with ejection suction of dust from the settling chamber: 1 – filter element; 2 – multi-cyclone; 3 – dust settling chamber

An electric fan drive system would be much more practicable, but it would put an extra load to the vehicle's electric power supply system. Moreover, the necessity of continuous fan operation would impose very stringent durability requirements on the fan drive system. Anyway, both of the fan drive system types would translate into an extra energy demand to be covered by the engine. Therefore, ejectors arranged in various configurations (Fig. 2) are commonly used in present-day designs of multi-cyclone air cleaners of IC engines for the extraction of dust from their settling chambers.

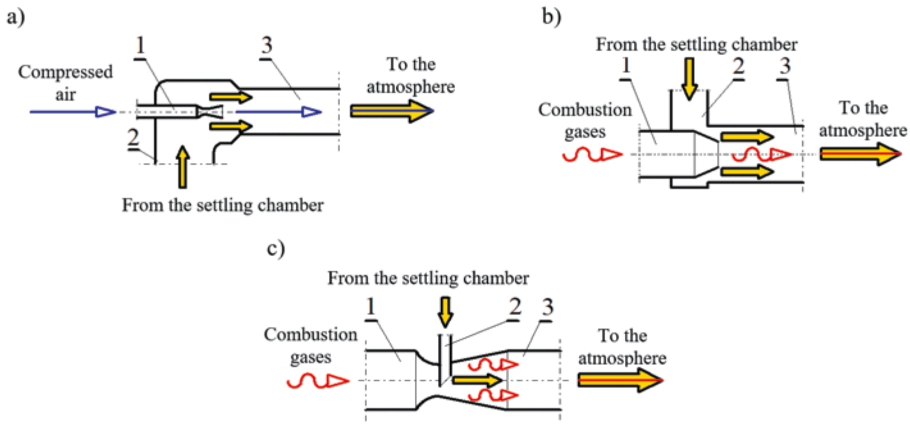

Fig. 2. Various ejector configurations used in dust extraction systems to induce an ejection stream: a) – operated by compressed air; b) and c) – operated by engine exhaust gases; 1 – motive (sucking) stream inlet; 2 – passive (sucked) stream inlet; 3 – mixing chamber [17]

In piston engines, the energy of the combustion gases discharged from the engine exhaust system is employed to operate the ejectors. In turbine engines, the energy of the compressed air supplied by the engine compressor may also be used. Thanks to simple construction, the ejector manufacturing costs are insignificant and the absence of moving parts makes the ejector a highly reliable device. The ejector configurations where combustion gases discharged from the engine are used as the motive (sucking) stream have been shown as versions b) and c) in Fig. 2. The motive stream, which forces gases to flow in the suction (passive) duct may also be a stream of compressed air (Fig. 2a). The dust extraction method based on the ejection effect is much more economical than the one where a fan or a blower is used, in terms of both energy consumption and manufacturing costs; it is characterized by high reliability, too.

The ejector configuration as shown in Fig. 2b has been realized in the ejection system of dust extraction from the air filter's settling chamber in tanks T-72 and PT-91 (Fig. 3). The system is provided with two ejectors connected by pipes with two outlet ports of the dust settling chamber. The ejectors (left and right) are incorporated in the exhaust systems of each engine cylinder block. A similar system of dust extraction from the multi-cyclone's dust settling chamber, but with a single ejector, has been provided in infantry fighting vehicle BWP and tracked vehicle 2S-1.

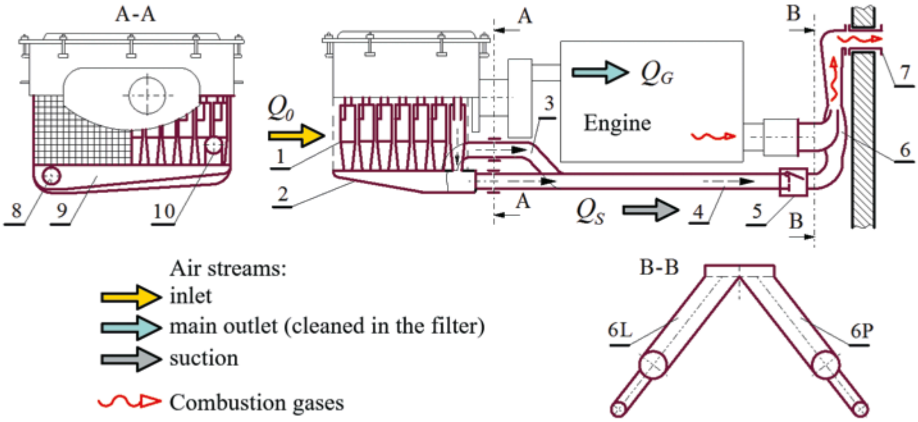

Fig. 3. Ejection system of dust extraction from the air filter's settling chamber of tank T-72:
1 – multi-cyclone; 2 – dust settling chamber; 3 and 4 – left and right dust extraction pipe; 5 – check valve;
6 – ejector (6L – left, 6P – right); 7 – exhaust pipe; 8 and 10 – left and right dust extraction port;
9 – end wall of the dust settling chamber

The ejector configuration shown in Fig. 2a is commonly used in the ejection systems of dust extraction from the air filter's settling chambers in helicopters (Fig. 4).

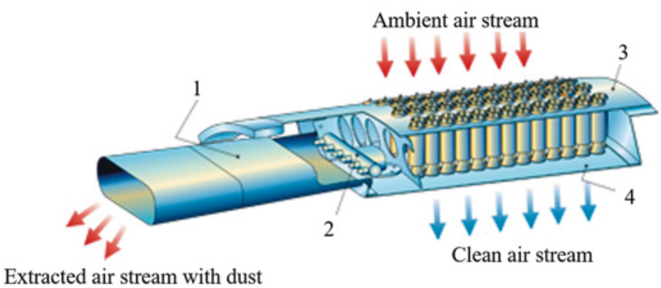

Fig. 4. Compressed air-operated ejection system of dust extraction from a helicopter's multi-cyclone air filter:
1 – suction tube; 2 – ejector; 3 – multi-cyclone; 4 – dust settling chamber [37]

To create an ejection sucking stream in the systems of dust extraction from the multi-cyclone's settling chamber, special electrically driven fans are also employed. Devices of this type are used in the systems of dust extraction from helicopter's air filters and in tank Leopard 2.

As it can be seen from the above, the most rational and popular method of inducing an airflow stream that would extract dust from the settling chamber of an air filter is the utilization of the stream of combustion gases discharged from the engine or a compressed air stream.

The continuous removal (by suction) of the dust separated by cyclones and accumulated in the multi-cyclone's settling chamber causes a noticeable growth in the filtration efficiency and, in consequence, a longer air filter service life limited by the predetermined value of the maximum acceptable filter restriction Δp_{fdop}.

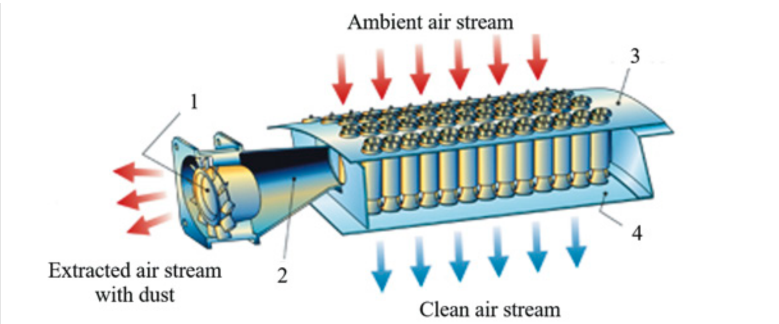

Fig. 5. Fan-operated ejection system of dust extraction from a helicopter's multi-cyclone air filter: 1 – suction tube; 2 – ejector; 3 – multi-cyclone; 4 – dust settling chamber [37]

This is confirmed by results of the tests carried out by the author where the filter restriction (Δp_w) and filtration efficiency (φ_w) characteristic curves were determined as functions of mass (m_D) of the dust drawn into the filter with the ambient air, i.e. $\Delta p_w = f(m_D)$ and $\varphi_w = f(m_D)$, respectively, for the filter barrier made of paper and operating in a "cyclone – filter element" system (Fig. 6). The removal (by suction) of the separated dust from the cyclone's settling chamber caused the filter element service life, limited by the maximum acceptable filter restriction value adopted as Δp_f = 6 kPa, to be extended by 75 %.

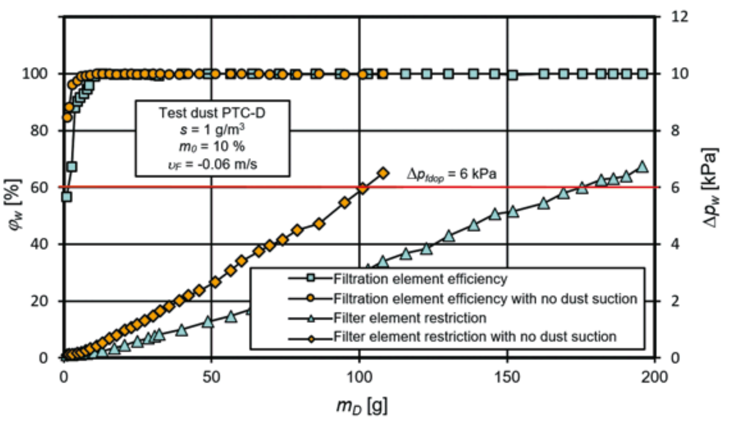

Fig. 6. Changes in the restriction (Δp_w) and filtration efficiency (φ_w) characteristics of a filter barrier made of paper and operating in a "cyclone – filter element" air cleaner system with and without ejection suction of dust from the cyclone's settling chamber, determined as functions of mass (m_D) of the dust drawn with ambient air into the system [13]

3. Impact of dust extraction on the efficiency of air filtration in a multi-cyclone

The use of a sucking stream for the removal of contaminants from the dust settling chamber produces a measurable effect in the multi-cyclone operation: it causes an increase in the air filtration efficiency. A measure of the suction intensity is the suction ratio m_0, usually defined as the percentage ratio of the suction stream value Q_S (Fig. 1) to the filter outlet stream (i.e. engine inlet stream) Q_G [2, 5, 7, 12, 15, 25, 29]:

$$m_0 = \frac{Q_S}{Q_G} \cdot 100\% \tag{1}$$

According to the publications dealing with this issue, the suction ratio most often falls within a range of m_0 = (5÷15) % [5, 6, 15, 18, 20]. In practice, the flow rate of the suction stream Q_S generally does not exceed 10 % of that of the filter outlet stream Q_G, as a further increase in the flow rate of the stream Q_S does not result in a considerable growth in the efficiency of air filtration in a multi-cyclone. Apart from that, an ejector placed in the engine exhaust system raises the restriction in the exhaust system. Of course, an increase in the flow rate of the suction stream will improve the filtration efficiency of the multi-cyclone, but this will require a change in the ejector characteristics, which will additionally raise the restriction in the exhaust system and, in consequence, cause a noticeable drop in the engine power output. At the suction ratio values of m_0 = (5÷15) % as commonly encountered, the said restriction is so small that the drop in the engine power output is insignificant. An excessive increase (by more than 15 %) in the flow rate of the suction stream will entail an increase in the filter dimensions that is required due to a growth in the flow rate of the filter inlet stream Q_0 by the value of the suction stream flow rate Q_S, according to equation (2):

$$Q_0 = Q_G + Q_S \tag{2}$$

A growth in the stream Q_0 without a change in the cross-sectional area of the cyclone inlet causes the multi-cyclone restriction to rise and, thereby, the engine power output to decline.

It is not easy to explain the impact of the dust extraction from the dust settling chamber of an inertial filter (multi-cyclone) on the filtration efficiency. This is because of the complexity of the aerosol motion in a cyclone. The contaminated gas caused to rotate moves in the first phase helically downwards to the conical section of the cyclone, forming an "outer vortex". This vortex is transmitted to the dust settling chamber, causing the dust present there and being separated from the gas to rotate, and then it begins to move helically back towards the cyclone outlet port, forming an "inner vortex". The change in the direction of vortex motion in the lower part of the cyclone generates a vacuum in the dust settling chamber.

In result of the formation of a suction stream Q_{Sc} in the cyclone, the stream Q_{0c} of the inlet air contaminated with dust, moving helically towards the bottom part of the conical section of the cyclone (outer vortex), does not fully turn back towards the cyclone outlet port as a return stream (inner vortex). Within the bottom area of the conical section of the cyclone, a radial vortex is generated, directed from the cyclone wall to its centreline and then towards the inlet to the dust settling chamber (Fig. 7). In consequence, a part of the air stream, amounting to Q_{Sc}, is separated and flows out of the conical section of the cyclone through a purging hole to the settling chamber, sweeping away the larger dust particles, thanks to which the filtration efficiency of the cyclone is raised.

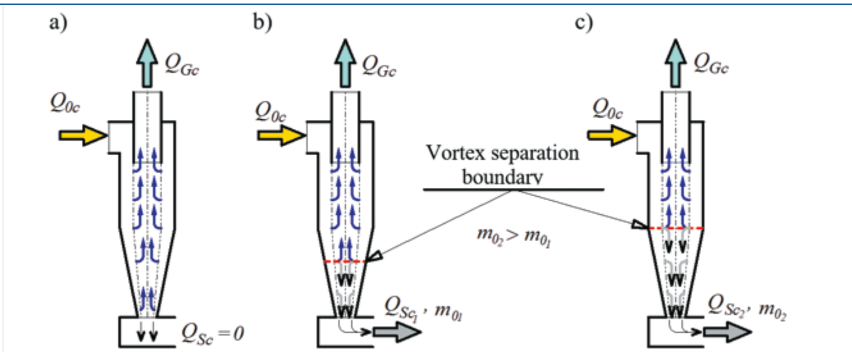

Fig. 7. The flow of air streams through a reverse-flow cyclone with tangential inlet: a) with no dust suction; b) and c) with dust suction of various intensity [13]; Q0c – inlet air stream; Q_{Sc} – suction stream; Q_{Gc} – clean air stream

An increase in the flow rate Q_{Sc} of the suction stream (i.e. in the dust suction ratio m_0) causes the hypothetical boundary separating the two vortexes from each other to be moved away from the purging hole (Fig. 7) and thus the volume of the cyclone portion affected by the suction stream is raised. Simultaneously, the axial velocity of the stream is growing within the bottom area of the conical section of the cyclone, which results in a growth in the velocity of motion of the dust particles present there towards the dust settling chamber. Hence, the content and size of the larger dust particles in the clean air outlet stream is steadily declining and the filtration efficiency of the cyclone is increasing.

The raising of the suction ratio value m_0 results in an intensive growth in the cyclone's filtration efficiency, but this growth only takes place until a specific limit is reached. For a uniflow cyclone with axial inlet, a change in the suction ratio value m_0 causes a steep growth in the cyclone's filtration efficiency, but this effect is only observed when this value is within a range of m_0 = (2÷10) % (Fig. 8). For a further growth in the suction ratio value, the increase in the cyclone's filtration efficiency is insignificant. A change in the suction ratio value within a range of m_0 = (2÷10) % causes the cyclone restriction to grow from 1.04 kPa to 1.42 kPa, i.e. by more than 35 %.

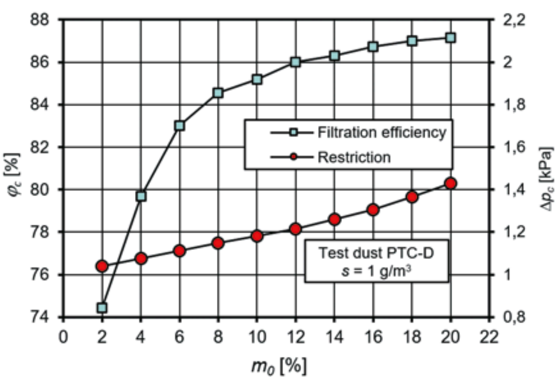

Fig. 8. Impact of the dust suction ratio m_0 on the filtration efficiency and restriction of a uniflow cyclone [16]

It can be seen from the filtration efficiency φ_c and accuracy d_{zmax} curves plotted in Fig. 9 for two uniflow cyclones that for the cyclone of the air filter used in the Scania engine of the KTO Rosomak special vehicle, the steep growth in the filtration efficiency φ_c takes place when the dust suction ratio is growing in the range of up to m_0 = 10 %, while for the cyclone of the air filter of the Volvo vehicle, the optimum value of the dust suction ratio is m_{0opt} = 16 %). An increase in the dust suction ratio results in an improvement in the filtration accuracy of the two cyclones under consideration. For the suction ratio growing from m_0 = 0 % to m_0 = 18 %, the maximum size of the dust particles penetrating through the filters drops from 30 μm to 17.4 μm and from 25 μm to 15.8 μm.

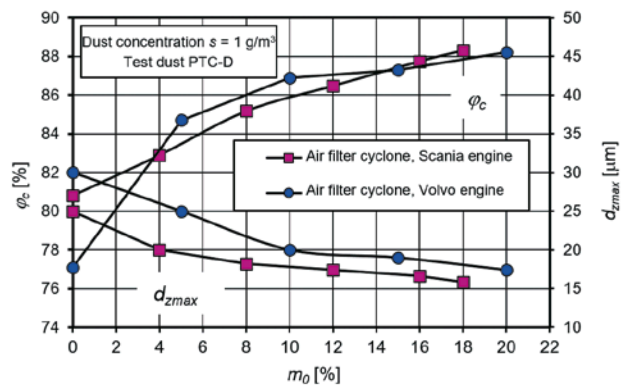

Fig. 9. Filtration efficiency (φ_c) and accuracy (d_{zmax}) curves for two uniflow cyclones as functions of the ratio of ejection suction of dust (m_0) [11]

Fig. 10 shows the impact of the dust suction ratio m_0 on the characteristic curves of air filtration efficiency $\varphi_c = f(Q_{Gc})$ and filter restriction $\Delta p_c = f(Q_{Gc})$ of a reverse-flow cyclone with tangential inlet D40 used in the multi-cyclones of tracked vehicles' air cleaners. The general shape of the curves $\varphi_c = f(Q_{Gc})$ and $\Delta pc = f(Q_{Gc})$ is typical of the cyclones of this type. The suction of dust from the cyclone's settling chamber causes almost parallel displacement of the characteristic curves towards higher values. A significant growth in the filtration efficiency of the reverse-flow cyclone with tangential inlet D40 takes place for the dust suction ratio m_0 changing in the range from 0 % to 8 % (Fig. 10).

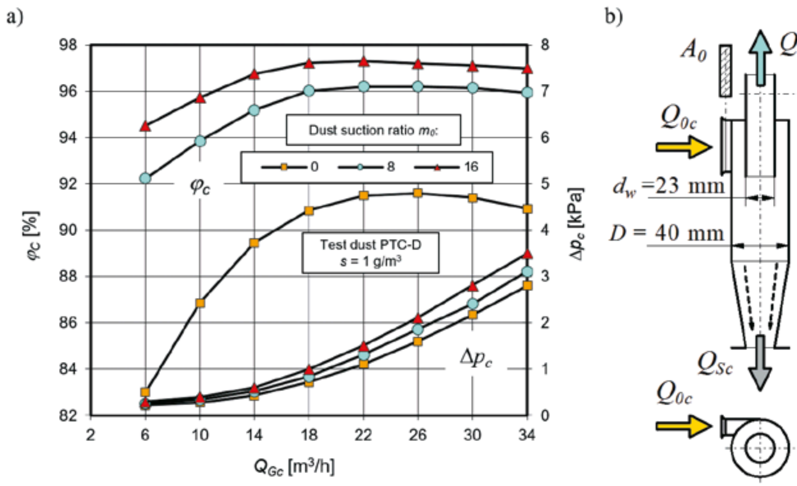

Fig. 10. The impact of the dust suction ratio m_0 on the characteristics of a reverse-flow cyclone with tangential inlet D40 [15]: a) filtration efficiency $\varphi_c = f(Q_{Gc})$ and filter restriction $\Delta p_c = f(Q_{Gc})$; b) functional schematic of the reverse-flow cyclone with tangential inlet D40

For the air stream flow rates of Q_{Gc} ranging from 6 m³/h to 34 m³/h and the ejection suction ratio of m_0 = 8%, the cyclone under test reached a filtration efficiency of φ_c = 96.2 %, which exceeded the figure achieved without suction by about 5 %. The raising of the ejection suction ratio by further 8 percentage points produced a growth in the filtration efficiency by as little as about 1 %. On the other hand, an increase in the ejection suction ratio results at the same time in a growth in the cyclone resistance Δp_c. An increase in inlet air stream Q_{0c} (by the Q_{Sc} value) translates into a growth in the velocity υ_0 of the air flow through the cyclone inlet port. Since the restriction Δp is a function of the square of flow velocity, i.e. $\Delta p_c = f(\upsilon_0^2)$, small changes in the inlet air flow velocity υ_0 result in significant changes in the Δp_c value.

The filtration efficiency $\varphi_c = f(Q_{Gc})$, filtration accuracy $d_{max} = f(Q_{Gc})$, and restriction $\Delta p_c = f(Q_{Gc})$ characteristic curves of the uniflow cyclone with axial inlet of the air filter used in the Volvo motor truck engine, taken with dust suction (at m_0 = 10 %) and with no dust suction, have been presented in Fig. 11.

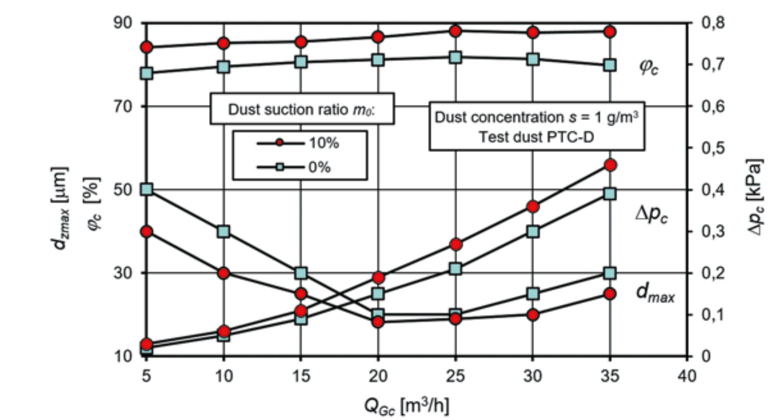

Fig. 11. Filtration efficiency $\varphi_c = f(Q_{Gc})$, filtration accuracy $d_{max} = f(Q_{Gc})$, and restriction $\Delta p_c = f(Q_{Gc})$ characteristic curves of a uniflow cyclone with axial inlet of the air filter used in the Volvo motor truck engine, taken with dust suction (at m_0 = 10 %) and with no dust suction [11]

At the ejection suction of dust with a ratio of m_0 = 10 %, the filtration efficiency curve $\varphi_c = f(Q_{Gc})$ takes higher values and only slightly differs in terms of its shape in comparison with the curve taken with no dust suction. The application of dust suction raised the filtration efficiency of the Volvo cyclone to φ_c = 88.1 %, i.e. by 7.7 %. Such a nature of the filtration efficiency curve $\varphi_c = f(Q_{Gc})$ is consistent with the information provided in the literature and with other cyclone test results [1, 3, 4, 6].

The test results presented reveal a considerable impact of the extraction of dust from the settling chamber on the filtration accuracy $d_{max} = f(Q_{Gc})$ of uniflow cyclones. The cyclone of the air filter used in the Volvo motor truck engine, when operating with no dust extraction, achieves the best filtration accuracy, i.e. d_{max} = 20 μm, at an air stream flow rate of Q_{Gc} = (20÷30) m^3/h. When the cyclone is operating at the air stream flow rates remaining within this range and with the ejection suction of dust at a level of m_0 = 10 %, the maximum size of the dust particles unseparated from the air stream is reduced to d_{max} = (18.2÷19) μm. Simultaneously, this is the range of the air stream flow rates Q_{Gc} at which the cyclone operates with its maximum efficiency. Both an increase and drop in the air stream flow rate outside of the range of Q_{Gc} = (20÷30) m^3/h results in a growth in the maximum dust particle size d_{max} with an insignificant reduction in the filtration efficiency.

With an increase in the air stream flow rate Q_{Gc}, a parabolic growth in the cyclone restriction Δp_c is observed, which is consistent with the cyclone operation theory. For the maximum value of the air stream flow rate of Q_{Gc} = 35 m^3/h, the restriction of the cyclone of the air filter used in the Volvo motor truck engine is Δp_c = 0.39 kPa without dust suction and Δp_c = 0.46 kPa with dust suction at a rate of m_0 = 10 %, which means a growth in the restriction by 18 %.

4. Unevenness of dust suction

An analysis of the available design solutions of multi-cyclones and the systems of dust extraction from their dust settling chambers shows that if the operating range of a dust settling chamber covers several ten cyclones and the dust is extracted from the settling chamber through one or two ports only, then [5, 6, 12, 15, 17, 19, 20, 36]:

- the suction stream flow rates of individual cyclones differ from each other;
- the whirled air streams flowing out of individual cyclones and entering the common dust settling chamber interact with each other;
- reverse flows may be generated in the outermost cyclones.

The above phenomena may cause the multi-cyclone's filtration efficiency to be lower than expected for the dust suction ratio adopted for individual cyclones. The test results that confirm this thesis have been presented in publications [5, 6, 15, 17].

Thus, the efficiency of multi-cyclone filters depends not only on correct selection of their design and airflow parameters but equally on the uniform aerosol distribution among all the cyclones and on the appropriate arrangement of the system that is to remove the dust having been separated. There is a lack of information in the literature available about any theoretical analyses and experimental research that would explain this problem.

The impact of the design of a multi-cyclone and its dust settling chamber on the values of the flow rates Q_{Sc} of the suction streams flowing out from individual cyclones was examined on the multi-cyclone incorporated in the air filter of the engine of the T 72 special vehicle.

The dust settling chamber of the multi-cyclone under test is a hollow structure, resembling a flat cuboid. The multi-cyclone includes 96 reverse-flow cyclones with tangential inlet, with D = 40 mm inside diameter each, mounted on a rectangular top panel of the dust settling chamber and arranged in rows and columns. The dust trapped in the settling chamber is sucked out at two points through tubular ports, situated on the end wall of the chamber and on the cyclone-mounting panel, see Fig. 12.

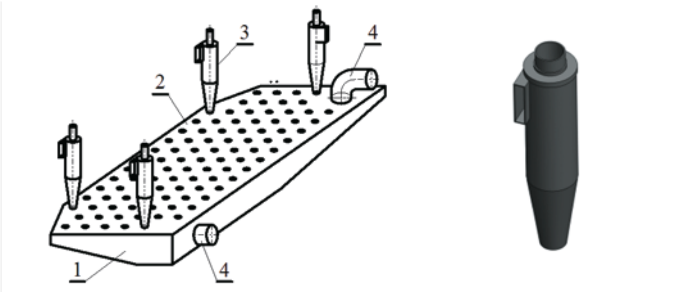

Fig. 12. Design of the multi-cyclone and dust settling chamber of the air cleaner of the T-72 special tracked vehicle: 1 – dust settling chamber; 2 – cyclone-mounting panel; 3 – cyclone; 4 – dust extraction ports

The values of the flow rates Q_{Sc} of the suction streams flowing out from individual cyclones of the air cleaner multi-cyclone were determined indirectly, by measuring the flow rate Q_{0c} of the cyclone inlet stream, which will take a value of $Q_{0c} = Q_{Sc}$ when the cyclone outlet stream flow rate is $Q_{Gc} = 0$. Such a case will take place when the outlet ports of all the cyclones are closed and a stream Q_{SF}, being a sum of the suction streams Q_{Sc} flowing out from individual cyclones, is sucked off from the multi-cyclone's dust settling chamber (Fig. 13).

$$Q_{SF} = \sum_{j=I}^{J} \sum_{k=1}^{K} Q_{Sc_{jk}} , \tag{3}$$

where: I, II, II, ...j, ...J – consecutive number of a cyclone in a column; J –number of rows;
1, 2, 3, ...k...K – consecutive number of a cyclone in a row; K –number of columns.

The values of the flow rates Q_{Sc} of the suction streams were determined from single outermost cyclones of the air cleaner multi-cyclone. The Q_{Sc} values cannot be thus determined from the cyclones situated in the middle part of the multi-cyclone. During the tests, the suction streams Q_{SF} flew in succession through the multi-cyclone's dust settling chamber with flow rates determined by the dust suction ratio values m_0 equal to 4 %, 8 %, and 16 % and by the nominal engine's air demand of $Q_{Sil} = Q_G$ = 3 400 m^3/h (0.944 m^3/s).

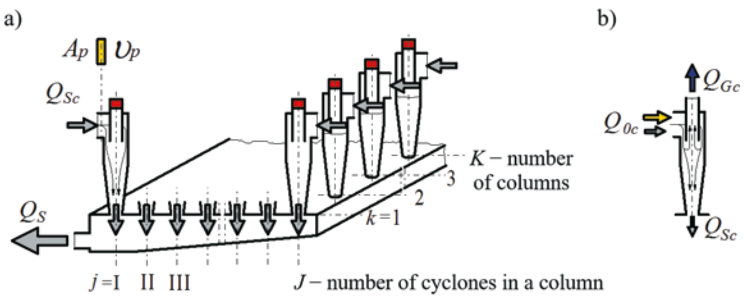

Fig. 13. The flow paths of streams Q_{Sc} in the cyclones: a) during measurements; b) during normal operation; I, II, II, ...j, ...J – consecutive number of a cyclone in a column; J – number of rows;1, 2, 3, ...k...K – consecutive number of a cyclone in a row; K – number of columns [15].

The values of flow rates Q_{Sc} of the suction streams flowing out from individual cyclones of the multi-cyclone differed very much from each other (Figs. 14-15). Regardless of the flow rate value Q_{SF} of the suction stream flowing out from the multi-cyclone's dust settling chamber, the highest Q_{Sc} values were recorded for the cyclones whose sucked stream outlets were close to the extraction ports of the multi-cyclone's dust settling chamber; they fell within a range of Q_{Sc} = (2.5÷5.95) m^3/h (Fig. 14). The flow rate values of the streams sucked off from the cyclones situated in the middle of the cyclone row under test and at a certain distance from the extraction ports were within limits of Q_{Sc} = (1.05÷2.95) m^3/h, i.e. they were lower by about 50 %. For the cyclones situated in the last row (VII), the flow rates of the streams sucked off from individual cyclones were lower by a half than those recorded for the first row (I) (Fig. 14). The differences between the maximum and minimum Q_{Sc} values were lower, too: for Q_{SF} = 540 m^3/h (0.15 m^3/s), 270 m^3/h (0.075 m^3/s), and 135 m^3/h (0.0375 m^3/s), the differences were equal to 11 %, 14 %, and 16 %, respectively.

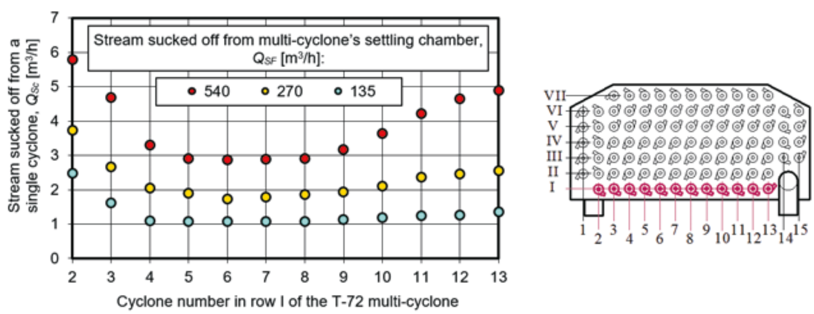

Fig. 14. Flow rate values Q_{Sc} of the streams sucked off from individual cyclones situated in row I of the T-72 multi-cyclone [15, 20]

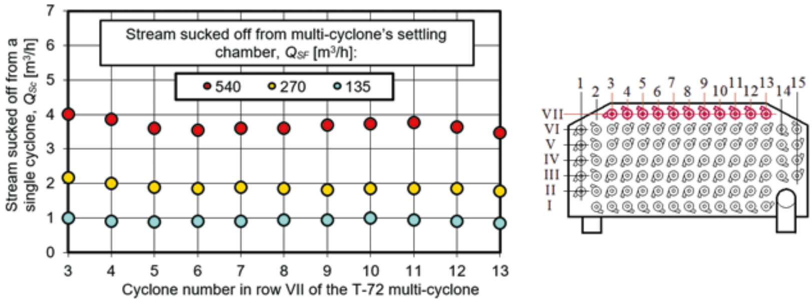

Fig. 15. Flow rate values Q_{Sc} of the streams sucked off from individual cyclones situated in row VII of the T-72 multi-cyclone [15, 20]

In a multi-cyclone consisting of a large number of cyclones and one common dust settling chamber provided with only one or two dust extraction ports, the dust suction outlets of individual cyclones are situated at various distances from the extraction ports of the settling chamber, in result of which the flow rates of the streams sucked off from individual cyclones naturally differ from each other and the filtration efficiency of individual cyclones and the multi-cyclone as a whole may thus be adversely affected. The results of tests carried out to explore such an effect have been presented in Fig. 18.

During the tests, a multi-cyclone comprising a set of uniflow cyclones with axial inlet was examined. The individual cyclones were mounted on the top panel of the dust settling chamber and arranged in three rows (I, II, and III) and six columns (1-6), Fig. 16.

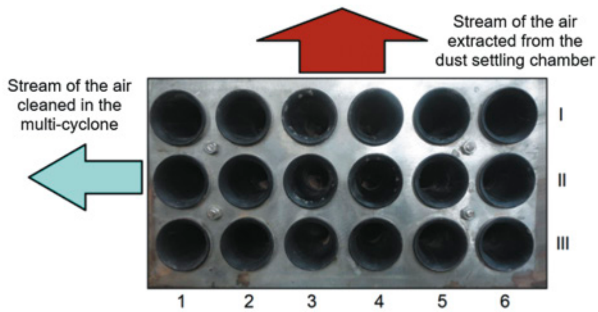

Fig. 16. Arrangement of individual cyclones in the multi-cyclone under test: I, II, III – numbers of cyclone rows; 1, 2, ..., 6 – numbers of consecutive columns (consecutive cyclones in a row)

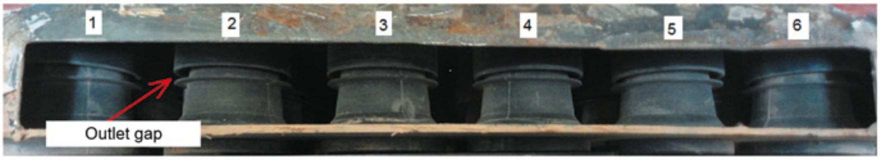

Fig. 17. Dust outlet ports of individual cyclones viewed from the dust settling chamber of the multi-cyclone (cyclone row I): 1, 2, ..., 6 – numbers of consecutive columns [8]

With an increase in the total mass of the dust having been drawn with the ambient air into the multi-cyclone, the filtration efficiency of the multi-cyclone is steadily decreasing; simultaneously, the lower the value of the dust suction ratio m_0, the more intensive drop in the filtration efficiency (Fig. 18). At the beginning of the multi-cyclone operation, when the dust suction ratio was m_0 = 20 %, the filtration efficiency value was φ_M = 86.25 % and when over 3 kg of dust had been fed to the multi-cyclone, the filtration efficiency of this unit dropped to φ_M = 61.72 %. When the multi-cyclone was operated at a dust suction ratio of m_0 = 5 %, the respective values were φ_M = 76.2 % at the beginning and φ_M = 24.2 % when the mass of the dust having been fed to the multi-cyclone reached a value of m_D = 2.17 kg. In this case, the filtration efficiency of the multi-cyclone dropped to one third.

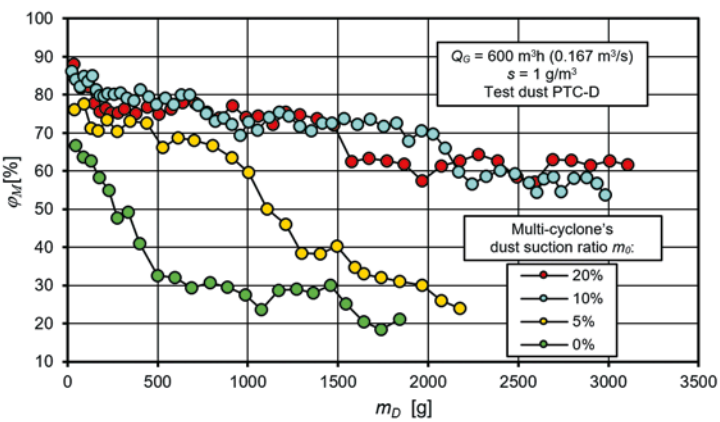

Fig. 18. Filtration efficiency of the multi-cyclone at various values m_0 of the ratio of ejection suction of dust from the settling chamber [8]

The observed phenomenon of a drop in the filtration efficiency of the multi-cyclone along with an increase in the mass of the dust having been fed to it together with the ambient air resulted from fact that the filtration efficiency a multi-cyclone as a whole was lower than it would be in the case of an identical set of individual cyclones operating separately with the same dust suction ratio. This effect was caused by the impact of differences in the flow ratio values of the streams sucked off from individual cyclones, interactions between the whirled air streams flowing out from individual cyclones, and a possibility of reverse flows occurring in the outermost cyclones in the multi-cyclone unit.

In result of the above factors, the following processes take place:

1) Dust is permanently deposited on the inner surfaces of the cyclone's outlet parts that form a gap through which the dust sucked off flows out. With the multi-cyclone operation time, the mass of the dust deposited in the gap is increasing, which hinders the outflow of the suction stream from the cyclone.
2) Dust is permanently deposited in the corners and on the peripheries of the settling chamber body, from where it is removed less effectively in comparison with the dust sucked off from the cyclones situated close to the appropriate extraction port. The dust deposit built up and lying on the bottom of the settling chamber hinders the outflow of both the dust having been sucked off and the air having been cleaned. In consequence, the values of the flow rate (velocity) of the air stream flowing through the cyclones decrease and, due to this, the filtration efficiency drops as well. With the multi-cyclone operation time, the mass of the dust deposited on the settling chamber bottom is increasing, which finally causes the outlet ports of the cyclones involved to be blocked and the cyclones not to function any more (Fig. 19).

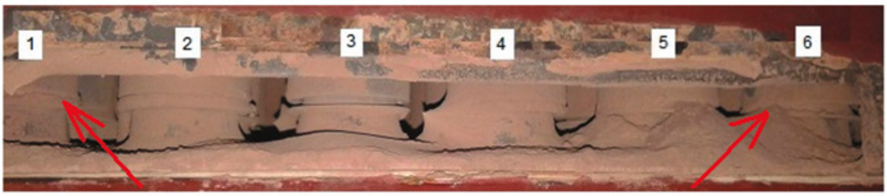

Fig. 19. Dust outlet gaps of individual cyclones, viewed from the multi-cyclone's dust settling chamber, after a period of air filter operation with a dust suction ratio of m0 = 5 %, during which 2 150 g of dust was fed to the filter: 1, 2, ..., 6 – numbers of consecutive cyclones in a row (the arrows indicate the cyclones whose outlet gaps were blocked with the dust) [8]

The intensity of the above processes, which reduce the multi-cyclone's filtration efficiency with increasing mass of the dust having been drawn into the filter, is raised when the ratio of dust suction from the settling chamber is lowered. The impact of this phenomenon on the performance characteristics of a barrier-type filter element made of nonwoven fabric AC-301, used as the secondary air filtration stage downstream of the multi-cyclone under test, has been illustrated in Fig. 20.

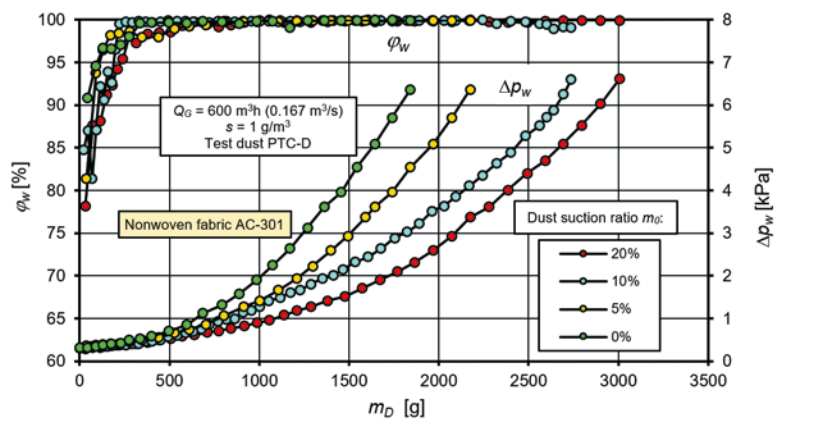

Fig. 20. Filtration efficiency and restriction of a filter element (nonwoven fabric AC 301) used as the secondary air filtration stage downstream of the multi-cyclone at various values m_0 of the ratio of ejection suction of dust from the settling chamber [8]

The filter restriction Δp_w steadily rises with increasing mass of the dust having been fed to the filter, which is consistent with the theory of filtration in barrier filters. The intensity of growth in the filter restriction Δp_w increases when the dust suction ratio value m_0 is lowered. Therefore, the maximum acceptable restriction value, adopted as Δp_{wdop} = 6 kPa, is reached by the filter element at various values of the dust mass having been drawn into the filter. If the multi-cyclone is operated at a dust suction ratio of m_0 = 20 %, then the restriction value of Δp_{wdop} = 6 kPa is reached by the filter element after the system has been fed with m_D = 2.9 kg of dust. At m_0 = 10 % and m_0 = 5 %, the corresponding values of the dust mass are m_D = 2.7 kg and mere m_D = 2.1 kg, respectively. When the multi-cyclone is operated with no dust extraction from the settling chamber, the filter element restriction value of Δp_{wdop} = 6 kPa is reached after the system has been fed with as little as m_D = 1.8 kg of dust, which is a figure lower by 40 % than that obtained for the multi-cyclone being operated at a dust suction ratio of m_0 = 20 %. Thus, the time of operation of the engine air filtration system until the maximum acceptable value Δp_{fdop} is reached is much shorter than that achievable when dust is sucked off from the multi-cyclone's settling chamber.

The phenomenon as described above is caused by a reduction in the multi-cyclone's filtration efficiency at a lower value of the ratio of dust suction from the settling chamber and by a drop in the multi-cyclone's filtration efficiency with the multi-cyclone operation time, i.e. with a growth in the total mass of the dust having been fed to the filtration system.

5. Possibilities of organizing the process of dust extraction from multi-cyclone air cleaners of motor vehicle engines

As learned from the experiments having been carried out, the main reason for the unevenness of the suction streams of individual cyclones may be the diversity of the resistance to flow of the streams in the filter's dust settling chamber between specific cyclones and the dust extraction port. The diversity is chiefly caused by different distances to be covered by individual streams, defined by the cyclone location in relation to the said port, the influence of the settling chamber walls on the streams sucked off from the cyclones situated close by, as well as the possible presence of areas of whirls in the combined airflow stream in the dust settling chamber.

Theoretical and experimental studies carried out with author's participation [5, 6] as well as author's own analyses and research works [12, 14, 15, 17-20] have resulted in the establishing of three basic methods aimed at the obtaining of relatively even streams sucked off from individual cyclones:

- Symmetrical arrangement of all the cyclones in relation to the dust extraction port;
- Equalization of the resistance to flow of the sucked streams by intentionally and appropriately choking the streams sucked off from the cyclones for which the resistance to flow is lower than that for the other ones;
- Combined method, i.e. a combination of the two methods specified above, obtained by appropriate engineering of the system design.

The only possible way to obtain a symmetrical arrangement of the cyclones is to place all of them on the circumference of a circle. In such a case, a free space is left in the central part of the cyclone-mounting panel, the bigger the more cyclones is incorporated in the filter (Fig. 21). Thus, the symmetrical arrangement of cyclones translates into large dimensions of the cyclone-mounting panel of the dust settling chamber. Usually, not too much free space is available in the vehicle's engine chamber; therefore, such a multi-cyclone design is hardly practicable.

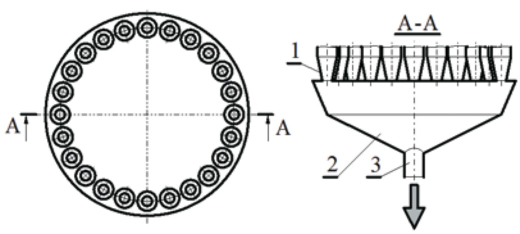

Fig. 21. Schematic of a dust settling chamber with a symmetrical arrangement of all the cyclones in relation to the dust extraction port: 1 – cyclone; 2 – dust settling chamber; 3 – dust extraction port

The resistance to flow of the streams sucked off from the cyclones may be equalized as follows, by appropriately choking and directing selected streams:

- by installing an intermediate inlet to the dust extraction port in the multi-cyclone's dust settling chamber;
- by dividing the dust settling chamber into separate ducts;
- with the use of special elements to choke the suction streams at the outlets of selected cyclones.

An intermediate inlet to the dust extraction port in the multi-cyclone's dust settling chamber may be made by introducing a specially shaped baffle (deflector) to this chamber, placed over the inlet to the dust extraction port. The deflector should ensure a desired distribution of the streamlines of the suction streams flowing out of individual cyclones. An example of such a solution, showing an axially symmetric dust settling chamber, has been presented in Fig. 22.

It should be emphasized here that the design solution as shown is difficult to be engineered because of the necessity of using a complex computation model and then carrying out complicated and time-consuming experimental tests.

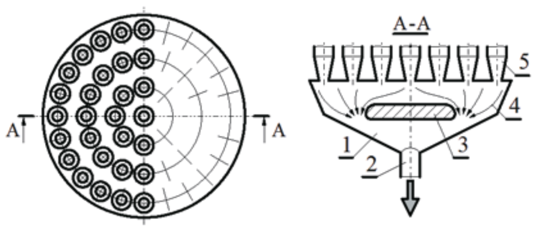

Fig. 22. Schematic of a dust settling chamber with an intermediate inlet to the dust extraction port: 1 – dust settling chamber; 2 – dust extraction port; 3 – baffle (deflector); 4 – streamlines of the suction streams; 5 – cyclone

In another method of equalizing the flow rates of the streams sucked off from individual cyclones, the dust settling chamber is divided by means of several partitions into separate suction ducts within the settling chamber, which are isolated from each other and assigned to (and serving) specific groups of individual cyclones (Fig. 23). The heights h_1, h_2, h_3 of the ducts thus formed by the partitions in the settling chamber should be appropriately selected for approximately equal duct restriction values to be obtained. Full equalization of the restriction values exclusively by computational selection of the duct geometry is not possible because the flows are relatively complicated. Therefore, the duct heights should be finally selected by experiment.

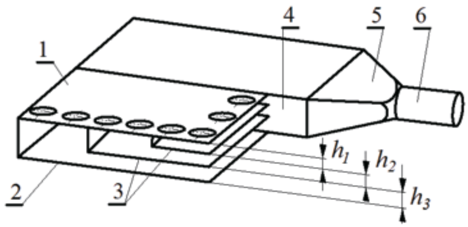

Fig. 23. Schematic diagram illustrating the idea of dividing a dust settling chamber into separate ducts: 1 – cyclone-mounting panel; 2 – settling chamber bottom panel; 3 – partitions; 4 – vertical wall; 5 – transition duct; 6 – dust extraction port

Each of the individual suction ducts in the dust settling chamber should cover a not very numerous group of cyclones. There may be 3 to 4 cyclones in a row within the duct width and 1 to 4 cyclones in a row within the duct length, depending on the duct height at the place where dust is sucked off from the cyclones. If there are more cyclones in a row within the filter width, then the dust settling chamber should be divided (Fig. 23) by an airtight vertical wall 4 into segments, the width of which should cover the required number of cyclones in a row. Each of the segments should be provided with a separate dust extraction port.

Unlike the dust settling chamber arrangements mentioned previously, the one presented above is much easier for being designed. The making of separate ducts is a solution particularly recommendable for modifying the dust settling chamber in the existing filters that are already in use but do not ensure adequate dedusting efficiency.

6. Recapitulation

In the motor vehicle engines that operate in conditions of high dust concentration in air (s = 1 g/m^3 or more), the intake air is filtered with the use of two-stage air cleaners, where an inertial filter (multi-cyclone) constitutes the primary filtration stage and the function of the secondary stage is performed by a paper filter element. The dust separated by the cyclones of the multi-cyclone unit is gathered in a common collector (container), referred to as dust settling chamber, from which it is then removed by a suction stream in a way based on the ejection effect. The most rational and popular method of inducing an airflow stream that would extract dust from the settling chamber of an inertial air filter is the utilization of the stream of combustion gases discharged from the engine or a compressed air stream.

The continuous removal (by suction) of the dust separated by cyclones and accumulated in the settling chamber of the inertial air filter (multi-cyclone) causes a noticeable growth in the filtration efficiency, but this effect can only be observed for suction ratio values of up to m_0 = 8-15 %. In consequence, the air filter service life limited by the predetermined value of the acceptable filter restriction Δp_{fdop} is extended, even by up to 50 %.

The ejection-based method of dust removal from the settling chamber of the multi-cyclone of a two-stage air cleaner serves its purpose, but it is not perfect.

If several ten identical cyclones connected in parallel and incorporated into a multi-cyclone operate with a common dust settling chamber then an air cleaner of this kind has a lower filtration efficiency than the total filtration efficiency of the same cyclones operating separately in identical conditions of aerosol flow. Such an effect may be caused by disturbances in the filtration process in result of uneven aerosol distribution among all the cyclones and reverse flows occurring between them. There is a lack of information in the literature available about any theoretical analyses and experimental research that would explain this problem.

If a multi-cyclone consisting of a large number (50-100 or more) cyclones has a common dust settling chamber provided with only one or two dust extraction ports then the distances between the outlets of the streams sucked off from individual cyclones and the dust extraction port are unequal. In consequence, the flow rates of the streams sucked off from individual cyclones that are deployed on a large area naturally differ from each other. This has an adverse impact on the operation of individual cyclones and the multi-cyclone as a whole, which manifests itself in the multi-cyclone's filtration efficiency steadily decreasing with the growing mass of the dust having been drawn into the filter with the ambient air, i.e. with the vehicle operation time; simultaneously, the lower the value of the dust suction ratio m_0, the more intensive drop in the filtration efficiency.

Such an effect is caused by the specific multi-cyclone design and imperfection of the system of dust extraction from the settling chamber. In the case under consideration, dust is permanently deposited in the corners and on the peripheries of the settling chamber body, from where it is removed less effectively in comparison with the dust sucked off from the cyclones situated close to the respective extraction port. The dust deposit built up and lying on the bottom of the settling chamber hinders the outflow of both the dust having been sucked off and the air having been cleaned and this may finally cause the outlet ports of the cyclones involved to be blocked and the cyclones not to function any more. The intensity of these processes is higher when the values of the dust suction ratio are low or when the multi-cyclone is operated without dust extraction from the settling chamber.

The restriction of the filter element used as the secondary filtration stage (and placed downstream of the multi-cyclone) grows more intensively, too. The intensity of growth in the restriction Δp_w of such a filter element increases with declining filtration efficiency and accuracy of the multi-cyclone, in consequence of which more dust, in terms of its mass, reaches the filter element per a time unit. In vehicle operation practice, this means that, at the predetermined value of the acceptable filter restriction Δp_{fdop}, the time between maintenance is shortened, which raises the frequency of the necessary maintenance operations and thus the vehicle operation costs.

The deposition of dust in the corners, on the peripheries of the settling chamber body, and in the dust outlet gaps in the outermost cyclones of the multi-cyclone unit may be prevented by appropriately designing the interior of the dust settling chamber. The chamber interior structure correctly designed may ensure the obtaining of equal flow rates of the streams sucked off from all the cyclones. The most rational and practicable method of ensuring the flow rates to be equal is the one oriented at equalizing the resistance to flow of the suction streams. The desired effects are obtained by appropriately changing the structure of the dust settling chamber, i.e. by dividing the chamber interior into separate segments and ducts that would cover specific groups of the cyclones.

In cyclone-type inertial filters consisting of several ten cyclones, the ejection suction may be organized in various ways. The selection of a specific method and solution to be adopted, aimed at the ensuring of equal flow rates of the streams sucked off from all the individual cyclones, depends not only on their filtration efficiency but also on the multi-cyclone form, number of the cyclones and configuration of the dust separator unit, space available for the installation of the unit, and possibilities of carrying out tests within an adequate scope.

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

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

References

[1] Baczewski K, Hebda M. Filtracja płynów eksploatacyjnych (Filtration of operating fluids). Radom MCNEMT, 1991/92.

[2] Cenrtisep Air Cleaner. Information materials published by PALL Corporation. USA, 2004.

[3] Diesel Engine Air Filtration. Information materials published by PALL Corporation. USA, 2004.

[4] Durst M, Klein G, Moser N. Filtration in Fahrzeugen. Information materials published by Mann+Hummel GmbH. Ludwigsburg, Germany, 2005.

[5] Dzierżanowski P, Dziubak T. Możliwości wykorzystania strumienia spalin wylotowych silnika tłokowego do odsysających układów ejekcyjnych odpylaczy bezwładnościowych powietrza wlotowego (Possibilities of utilizing the stream of combustion gases discharged from a piston engine in the ejection suction systems of inertial dust separators of intake air cleaners). Zakopane, KONES '96.

[6] Dzierżanowski P, Dziubak T. Układ filtrujący powietrza z ejekcyjnym odsysaniem pyłu silnika samochodu ciężarowego (Motor truck engine's air filtering system with ejection suction of dust). 6th International Symposium of the Institute of Motor Vehicles, Military University of Technology, Warszawa – Rynia. 1996.

[7] Dzierżanowski P. Bezwładnościowy odpylacz modułowy (Inertial dust separator of modular design). Bulletin of the Military University of Technology. 1986 (XXXV); 2 (402).

[8] Dziubak T. The effects of dust extraction on multi-cyclone and non-woven fabric panel filter performance in the air filters used in special vehicles. Eksploatacja i Niezawodnosc – Maintenance and Reliability. 2016 (18); 3: 348-357.

[9] Dziubak T. Operating fluids contaminations and their effect on the wear of elements of a motor vehicle's combustion engine. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2016; 2: 43-72.

[10] Dziubak T, Szwedkowicz S. Experimental research on nonwoven filter fabric for intake air filtration in the IC engine of an off-road vehicle. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2014; 4: 3-22.

[11] Dziubak T. 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. 2013; 2: 201-217.

[12] Dziubak T. The assessment of the possibilities of improvement of the extraction evenness, in multicyclone dedusters fitted in special vehicles. Combustion Engines – Silniki Spalinowe. 2012; 4 (151): 34-42.

[13] Dziubak T. Filtracja powietrza wlotowego do silników spalinowych pojazdów mechanicznych (Intake air filtration in internal combustion engines of motor vehicles). Military University of Technology. Warszawa. 2012: 122-127.

[14] Dziubak T. Analiza możliwości poprawy równomierności odsysania pyłu z odpylacza multicyklonowego (A study on the improvement of uniformity of dust extraction from multicyclone dust collectors). Combustion Engines – Silniki Spalinowe. 2011; 4 (147): 69-78.

[15] Dziubak T. Analiza procesu filtracji powietrza wlotowego do silników pojazdów specjalnych (Study on the process of intake air filtration in internal combustion engines of special vehicles). Postdoctoral dissertation. Military University of Technology. Warszawa. 2008.

[16] Dziubak T. Badania eksperymentalne cyklonu przelotowego do dwustopniowego filtru powietrza silnika czołgowego (Experimental tests of paning cyclone for tank engine two-stage air filter). Bulletin of the Military University of Technology. 2002 (LI); 5 (597): 151-168.

[17] Dziubak T. Badanie możliwości poprawy efektywności filtracji wielostopniowych filtrów powietrza wojskowych pojazdów mechanicznych (A study on the improvement of filtration efficiency of air cleaners in military motor vehicles). Report of the implementation of research project No. 0 T00A 003 14 sponsored by KBN (National Research Committee). Military University of Technology. Warszawa. 2001.

[18] Dziubak T. Problemy odsysania pyłu z multicyklonu filtru powietrza silnika pojazdu mechanicznego eksploatowanego w warunkach dużego zapylenia powietrza (The dust sucking-off from the air filter multicyclone of the vehicle engine exploited in high pollution concentration conditions). Zagadnienia Eksploatacji Maszyn PAN. 2001; 1 (125): 127-178.

[19] Dziubak T. Badania możliwości poprawy efektywności odsysania pyłu z odpylacza multicyklonowego silnika wojskowego pojazdu gąsienicowego (Improvement possibility of efficiency of dust sucking-off from multicyclone dust chamber of caterpillar-wheel vehicle engine). Bulletin of the Military University of Technology. 2000 (XLIX); 7 (575): 137-151.

[20] Dziubak T. Badania eksperymentalne ejekcyjnego układu odsysania zanieczyszczeń z filtru powietrza (Experimental research of sucking-off ejection system of polutions from the air filter). Bulletin of the Military University of Technology. 1998 (XLVII); 10 (554): 17-32.

[21] Dziubak T. Zapylenie powietrza wokół pojazdu terenowego (Dust concentration in the air surrounding an off-road vehicle). Wojskowy Przegląd Techniczny. 1990; 3.

[22] Fitch J. Clean Oil Reduces Engine Fuel Consumption. Practicing Oil Analysis Magazine. 2002; 11-12.

[23] 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.

[24] Graham K, Ouyang M, Raether T, Grafe T, McDonald 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.

[25] Greenfield R. R. The Use of Cyclones for Control of Solids Emission from Fluidised Bed Boilers. Filtration & Separation. 1986 (22); 1.

[26] 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. 2008 (15); 3.

[27] Jaroszczyk T. Air Filtration in Heavy-Duty Motor Vehicle Applications, Proc. Dust Symposium III Vicksburg MS. September 15-17, 1987.

[28] Jaroszczyk T. Problemy filtracji powietrza w silnikach spalinowych eksploatowanych w ciężkich warunkach (Problems of air filtration in internal combustion engines operated in difficult conditions). Silniki spalinowe. 1978; 2.

[29] Kim H T, Zhu Y, Hinds W C, Lee K W. Experimental study of small virtual cyclones as particle concentrators. Journal of Aerosol Science. 2002 (33); 5.

[30] Mann+Hummel Air Cleaners. Available from: www.mann-hummel.com.

[31] Siuta T. Studium problemu usprawnienia procesu filtrowania paliwa w silniku wysokoprężnym (A study on the problem of improving the process of fuel filtration in a compression ignition engine). Series: Mechanics. A monograph 330. Cracow University of Technology. 2006.

[32] Schaeffer J W, Olson L M. Air Filtration Media for Transportation Applications. Filtration & Separation. 1998 (35); 2.

[33] Szczeciński S et al. Turbinowe napędy samochodów (Turbine drive systems for motor vehicles). WKŁ. Warszawa. 1974.

[34] Truhan J. Filter Performance as the Engine Sees It. Filtration & Separation. 1997 (34); 12.

[35] Ward G. Nanofibres: media at the nanoscale. Filtration & Separation. 2005 (42); 7.

[36] Warych J. Oczyszczanie gazów – procesy i aparatura (The cleaning of gases: processes and equipment). WNT. Warszawa. 1998.

[37] www.pall.com/pdfs/Aerospace-Defense-Marine/Mil_Mi_Centrisep_Brochure_AEMILMIENb_pdf.

[38] www.pall.com/pdfs/Aerospace-Defense-Marine/AECH47SEN.pdf.