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POTENTIAL DESIGN IMPROVEMENTS OF A REVERSE FLOW MINI-CYCLONE WITH A TANGENTIAL INLET

Tadeusz Dziubak*

Faculty of Mechanical Engineering, Military University of Technology,
ul. Gen. Witolda Urbanowicza 2, 00-908 Warsaw, Poland

This paper presents an effect of general dimensions of a reverse flow mini-cyclone with a tangential inlet on its separation efficiency. Several mini-cyclone design modifications are presented and evaluated for use in the air filtration systems of motor vehicles. Local design improvements of three components of a reverse flow mini-cyclone with a tangential inlet D-40 of an air filter fitted in an all-terrain vehicle engine were introduced. An asymmetric curvilinear shape of an outlet port was used instead of a symmetrical shape. An outlet vortex finder inlet port shape was streamlined, and a cylindrical outlet vortex finder of the cyclone was replaced with a conical one. Experimental evaluation of the effects of the design improvements of mini-cyclone on its separation efficiency and performance as well as flow resistance was carried out. Separation efficiency of the cyclone was determined using the mass method as a product of dust mass retained by the mini-cyclone and supplied to the mini-cyclone in a specified time. Separation performance of the cyclone was determined as the largest dust particle $d_z = d_{zmax}$ in a specific test cycle in the cyclone outlet air stream. A polydisperse PTC-D test dust used in Poland, a substitute for AC-fine test dust was used. Dust concentration at the mini-cyclone inlet was kept at 1 g/m^3. The size and total number of dust particles in the air stream at the outlet of the original mini-cyclone and at the outlet of the improved mini-cyclone was determined using a particle counter.

Keywords: air filter, mini-cyclones, separation efficiency, separation performance, flow resistance, dust particle size distribution

1. INTRODUCTION

A supply of a dust-free inlet air to internal combustion engines of motor vehicles and machines to reduce friction and improve machine life has always been a major operational and design issue, in particular for vehicles operating in heavy dust conditions (approx. concentration above 1 g/m^3). The conditions generally apply to special military vehicles (tanks, land attack vehicles, self-propelled guns and special purpose vehicles) with high-power diesel engines at a maximum air demand Q_{eng} over 1 kg/s, e.g. $Q_{eng} =$ 1.21 kg/s, (3400 m^3/h) for T-72 tank engine, $Q_{eng} = 2.15$ kg/s (6000 m^3/h) for Leopard 2 tank engine (Durst et al., 2005) and $Q_{eng} = 5.36$ kg/s (15000 m^3/h) for Abrams tank engine (Honeywell International, 2000). For dust level concentration $s = 1$ g/m^3, often observed in vehicle use on the testing grounds, the engines 0.94 g/s, 1.67 g/s and 4.15 g/s of air, respectively (Dziubak, 2009).

Two-stage air filters with a multi-cyclone and a porous screen (a filter element usually made of paper) are often used to remove the high amount of dust with particle size < 100 μm (Baczewski and Hebda, 1992; Cenrtisep Air Cleaner, 2004; Durst et al., 2005; Dzierżanowski et al., 1985) from the air stream.

* Corresponding author, e-mail: tadeusz.dziubak@wat.edu.pl

The multi-cyclone is a unit including up to several hundred liners of the diameter up to $D = 40$ mm, also called mini-cyclones (as distinct from industrial cyclones, go with internal diameter of $D = 250-3000$ mm), arranged side-by-side in parallel on two common perforated plates (top and bottom). The cyclones used in motor vehicles achieve up to 98% separation efficiency (Baczewski and Hebda, 1992; Cenrtisep Air Cleaner, 2004; Dziubak, 2010; Dziubak, 1995). During the 8-hour operation of T-72 tank engine in testing ground conditions, the multi-cyclone may capture over 25 kg of dust, which is further removed by the ejector suction system (Dziubak, 2012; Dziubak, 2000).

High mini-cyclone performance, determined by a high separation efficiency φ and low flow resistance Δp, increases with an air flow rate and – general dimension ratio (e.g.: H/D, D/d_w, h/d_w, a/b, A_w/A_0) carefully determined based on many years of research (Hoffmann et al., 1991; Juda, 1968; Kabsch, 1992; Swift, 1986; Warych, 1998). The research showed a relation between general dimensions of the mini-cyclone and allowed to determine the effect of different dimensions on separation efficiency and flow resistance, as well as the typical range of geometrical parameters (a ratio of general dimensions) for which the mini-cyclone achieves optimum performance, i.e. maximum efficiency and minimum pressure drop. As shown in an example (Fig. 1), the changes in separation efficiency φ_c and coefficient of flow resistance ξ_c as a function of dimensionless ratios A_w/A_0 and H/d_w, the optimum values for those parameters range from 1.5–2 to 7–9, respectively (Juda, 1968).

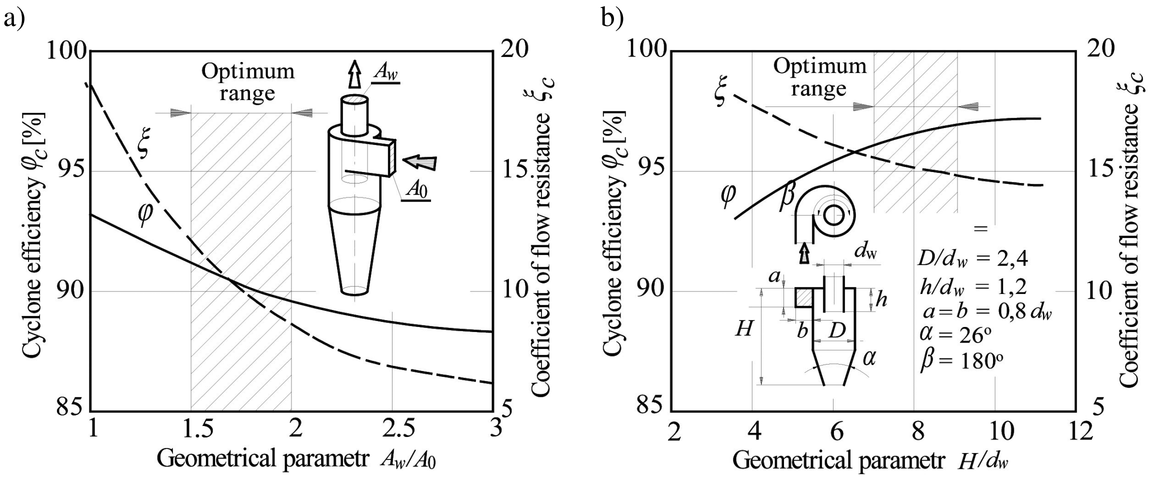

Fig. 1. Separation efficiency φ_c and coefficient of flow resistance ξ_c of mini-cyclones as a function of: a) with a tangential inlet A_w/A_0 and b) with a spiral inlet design H/d_w parameter (Juda, 1968)

The coefficient of flow resistance ξ_c is defined by the following relation (Juda, 1968):

$$\xi_c = \frac{2\Delta p_c}{\rho_a \cdot \upsilon_0^2} \tag{1}$$

The use of the above data in design of mini-cyclones guarantees a relatively high separation efficiency of micron-size particles from inlet air supplied to internal combustion engines.

Research on the improvement of aerosol particle separation efficiency in mini-cyclones and limiting the resistance of air flow via design modification without changes in general dimensions is still being carried out. The methods to improve mini-cyclone efficiency presented in literature (Dzierżanowski et al., 1985; Jo et. al., 2000; Jung et al., 2004; Kabsch, 1992; Lim et al., 2003; Lim et al., 2004; Yoshida et al., 2005; Zhu et al., 2001), although verified by laboratory tests, have not been verified in practice, thus additional analyses and tests are required. Numerical tests with CFD software are commonly used (Azadi and Azadi, 2012; Bernardo et al, 2006; Chu et al, 2011; Cortés and Gil, 2007; Jiao et al, 2006; Karagoz et al., 2013; Kobyłecki, 2011; Krasiński, 2007; Liu et al., 2006; Sakura and Leung, 2015; Wang et al., 2006; Wasilewski and Duda, 2016; Winfield et al., 2013; Qian et al., 2006) to assess cyclone efficiency, although experimental testing is considered the most reliable method (Baczewski and Hebda, 1991/92; Dzierżanowski et al., 1985; Dziubak, 2010; Jo et al., 2000; Lim et al., 2003; Wasilewski and Duda, 2016; Yoshida et al., 2005; Zhao, et al., 2004).

This paper presents an experimental assessment of separation efficiency, separation performance and flow resistance of modified designs of the reverse flow mini-cyclone with a tangential inlet used in off-road vehicle air filter's multi-cyclone.

2. POTENTIAL IMPROVEMENT OF CYCLONE SEPARATION EFFICIENCY

The improvements in efficiency of the reverse flow mini-cyclone with a tangential inlet (separation efficiency or reduction of flow resistance), without affecting general dimensions have been subject of many research works, which led to the following three methods of cyclone modification:

- modification of inlet stream feed method to the cylindrical cyclone section (Cortés and Gil; Dzierżanowski et al., 1985; Lim et al., 2003; Yoshida et al., 2005; et al., 2004),
- modification of outlet line shape to reduce flow resistance (Kabsch, 1992; Lim, et al., 2004),
- non-standard modified designs (Jo, et al., 2000; Jung et al., 2004, Zhu et al., 2001).

Dzierżanowski et al. (1985) showed that the symmetrical inlet nozzle with rounded edges, commonly used in reverse flow mini-cyclones with a tangential inlet results in adverse cross-sectional mass distribution of dust particles (Fig. 2a) that may affect separation efficiency. Replacing the symmetrical inlet with an asymmetrical inlet (Fig. 2b) or use of guide vanes 'K' (Fig. 2c) directly upstream of the inlet will directly (at the inlet) cause a significant amount of dust distributed close to the external wall of cylindrical section of a mini-cyclone to facilitate dust separation from air and improve separation efficiency.

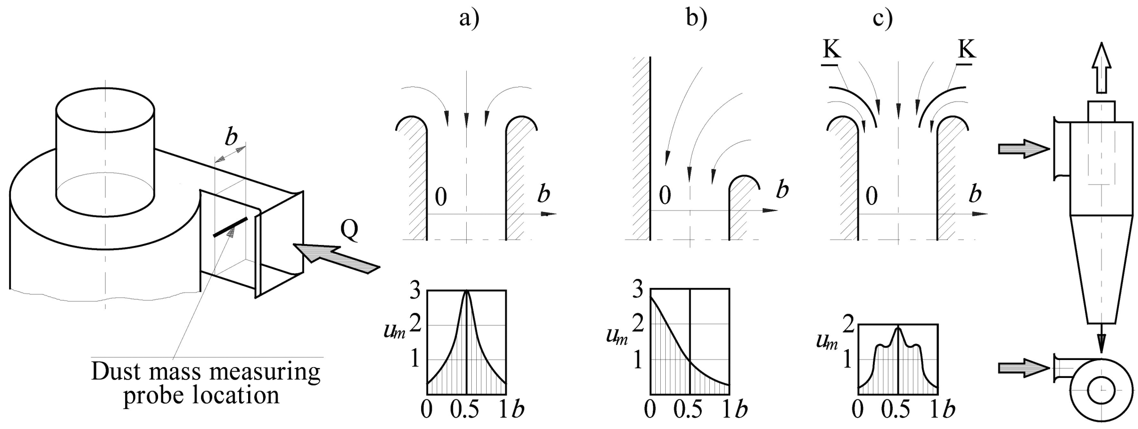

Fig. 2. Cross-sectional dust particle size distribution – flat inlet: a) symmetrical, b) asymmetrical, c) symmetrical with guide vanes u_m – relative dust fraction in the inlet air stream (Dzierżanowski et al., 1985)

All available research studies show that the highest share (75−90%) in total gas pressure losses for the cyclone are the losses at the inner cyclone vortex finder (outlet line) (Kabsch, 1992; Lim et al., 2004). There are several inner cyclone vortex finder solutions available to reduce flow resistance. Fig. 4 shows some examples.

Replacing a standard cylindrical outlet vortex finder with a conical outlet vortex finder while maintaining the inlet port diameter d_w and introducing a streamlined outlet vortex finder inlet port (Fig. 3b, c) may significantly reduce cyclone flow resistance without affecting the separation efficiency.

The other method to reduce cyclone flow resistance is to use special guide vanes (Fig. 3d) inside the outlet vortex finder, changing the kinetic energy of spiral gas movement inside the vortex finder to the kinetic energy of a straight flow along the vortex finder. The available literature does not cover any of the above solutions.

Besides a standard cylindrical outlet vortex finder, a conical vortex finder may be used, provided that the length and inlet port diameter d_w do not change (Fig. 3). Assuming that the conical outlet vortex finder is a diffuser, an optimum angle of flare is $\alpha_s = 7°C$ (Bukowski, 1968). For the α_s angle value, the stream does not separate from the wall, no vortices are formed, and the coefficient of flow resistance ξ_c has the lowest value.

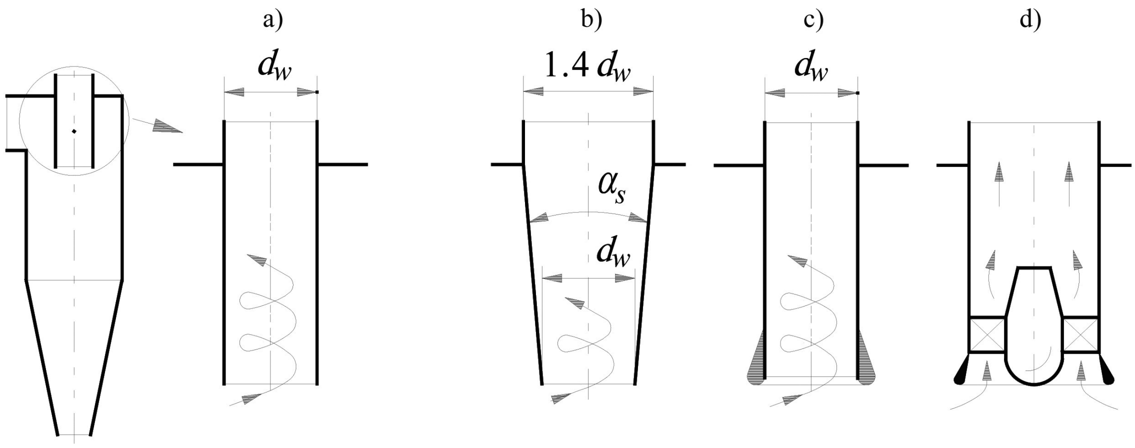

Fig. 3. Available shapes of an inner mini-cyclone vortex finder: a) cylindrical vortex finder – standard, b) cylindrical vortex finder with streamlined inlet port, c) conical vortex finder, d) vortex finder with guide vanes (Kabsch, 1992)

A streamlined outlet vortex finder's inlet port (Fig. 4) eliminates the contraction effect caused by the air inflow to the sharp-edged port. The contraction effect reduces the apparent cross-section area A_k of the main stream, which as a result is lower than the total cross-section area of inlet port A_w. The flow rate is increased, and thus the flow resistance increases.

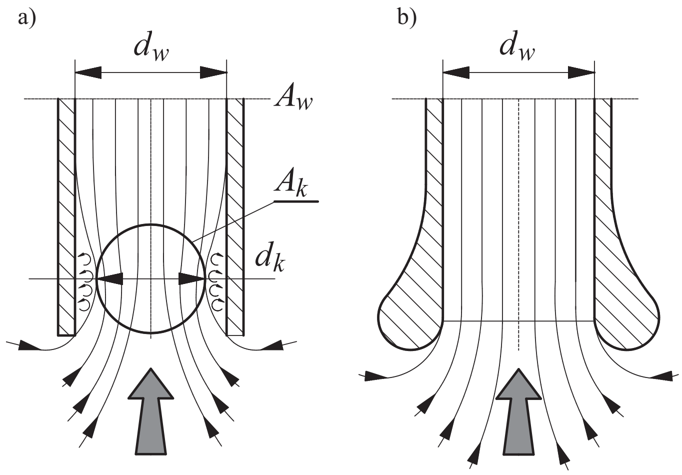

Fig. 4. Air inflow to the cylindrical vortex finder: a) sharp-edged inlet port, b) streamlined inlet port

Lim, et al. (2004) presents test results for reverse flow mini-cyclone with a tangential inlet ($D = 30$ mm) with outlet vortex finders of the same length but with different shape: cylindrical, $d_w = 15$, $d_w = 11$, $d_w =$

7 mm diameter with convergent and divergent cones, $h_s = 10$, $h_s = 25$, $h_s = 45$ cone length, $d_1 = 7$ mm and $d_2 = 15$ mm diameter on both cone sides, Fig. 5. The separation efficiency of various mini-cyclone versions was determined using a monodisperse test dust polystyrene latex (PSL, Duke Scientic Corp.) particles, with a density of 1.05 g/cm^3, generated using a commercial atomizer (TSI Inc., Model 9302) at two different air stream $Q = 30$ dm^3/min and $Q = 50$ dm^3/min values. The mini-cyclones with conical outlet vortex finders showed higher separation efficiency compared to mini-cyclones with a cylindrical outlet vortex finder with $d_w = 15$ mm diameter and lower efficiency compared to mini-cyclones with a cylindrical outlet vortex finder with $d_{w=}7$ mm diameter. The cone height does not significantly affect the separation efficiency and flow resistance of the mini-cyclone.

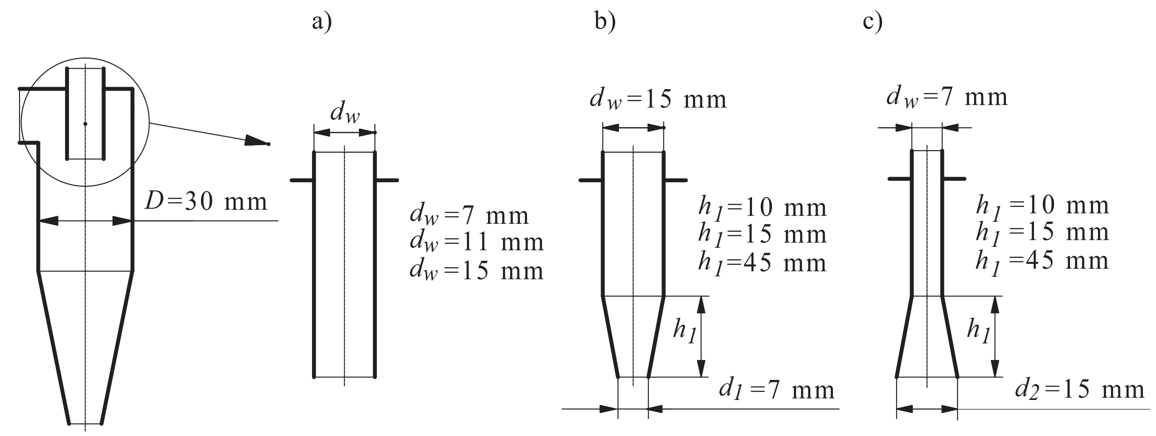

Fig. 5. Available cylindrical outlet vortex finder shapes: a) cylindrical vortex finders, b) convergent inlet vortex finders, c) divergent inlet vortex finders (Lim et al., 2004)

A modification of the outlet vortex finder, due to its simple design can be implemented in existing mini-cyclones in multi-cyclones used in air filtration systems of motor vehicles.

A new, non-standard method to increase cyclone separation efficiency was used by Yoshida et al. (2005). An additional tangential port supplying a stream of clean compressed air with the flow rate of $q = 0{-}210$ dm^3/min was used in a reverse flow mini-cyclone with a tangential inlet with $D = 72$ mm diameter with the following condition: $Q + q = \text{const} = 630$ dm^3/min. By changing the position of the additional outlet along the cylindrical section height, the highest separation efficiency was achieved when both outlet ports were in the same position at the top of the cylindrical section with the symmetry axis in parallel at an angle $\theta = 180°$ – Fig. 6. An increase in additional air stream of $q = 0{-}210$ dm^3/min resulted in an increase in cyclone separation efficiency ranging from $\varphi_c = 93.2\%$ to $\varphi_c = 98.1\%$.

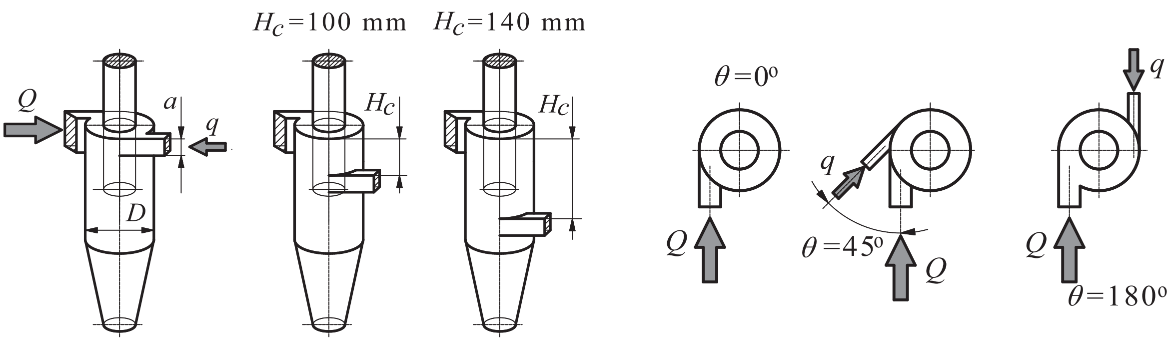

Fig. 6. Reverse flow mini-cyclone with a tangential inlet with additional inlet port in its cylindrical section (Yoshida et al., 2005)

To prevent transfer of gas swirling motion to the cyclone dust collector and lifting separated dust upwards in the secondary vortex, cyclones are fitted with a cone in the dust discharge port (Kabsch, 1992; Warych, 1998). The method is recommended for cyclones without dust collector suction systems and for "short cyclones", i.e. low height H to diameter D ratio (high-throughput cyclones).

Multi-cyclones in modern motor vehicles (in particular special purpose vehicles) feature a suction system, and therefore a cone at the dust discharge port is not required.

The analysis shows that:

1. It is possible to improve cyclone efficiency by reducing its flow resistance or increasing its separation efficiency by design modification without any change in general dimensions.
2. The cyclone modifications presented in the literature were introduced to single cyclones and tested for use in industrial applications.
3. No modifications were presented for a mini-cyclone used in air filtrations systems of motor vehicles.
4. To modify the mini-cyclones in multi-cyclones used in the first filter stage of motor vehicles, the following solutions may be used:
   - change in cross-section geometry and inlet port shape,
   - design of vortex finder comprising the geometry of its inlet port and vortex finder shape.

3. MODIFICATION OF A MINI-CYCLONE USED IN AIR FILTRATION SYSTEMS OF MOTOR VEHICLES

The modifications of mini-cyclone design were analysed for practical use in a D-40 type reverse flow mini-cyclone with a tangential inlet (Fig. 7) commonly used in air filter multi-cyclones utilized in special purpose vehicles.

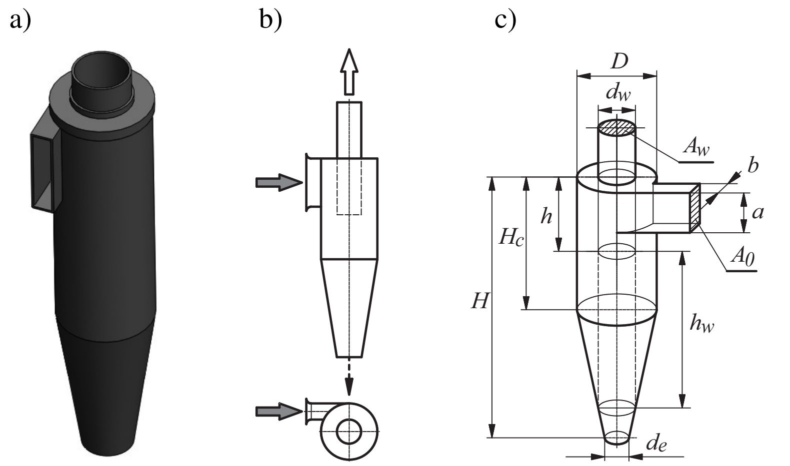

Fig. 7. D-40 type reverse flow mini-cyclone with a tangential inlet: a) general view, b) functional diagram, c) characteristic dimensions (H – 180 mm, H_c – 110 mm, h – 55 mm, D – 40 mm, d_w – 23 mm, d_e – 20 mm, A_0 – 320 mm^2, A_w – 430 mm^2, a – 40 mm, b – 8 mm)

Due to its simple design, D-40 type reverse flow mini-cyclone with a tangential inlet, seems more susceptible to design modifications to increase separation efficiency or reduce flow resistance. The design modifications must not affect general mini-cyclone dimensions, since it may have the opposite effect.

D-40 mini-cyclone design was modified as follows:

- asymmetric curvilinear shape of the outlet port instead of symmetrical shape (Fig. 8),
- streamlined outlet vortex finder's inlet port (Fig. 9),
- conical outlet vortex finder d_w (Fig. 10).

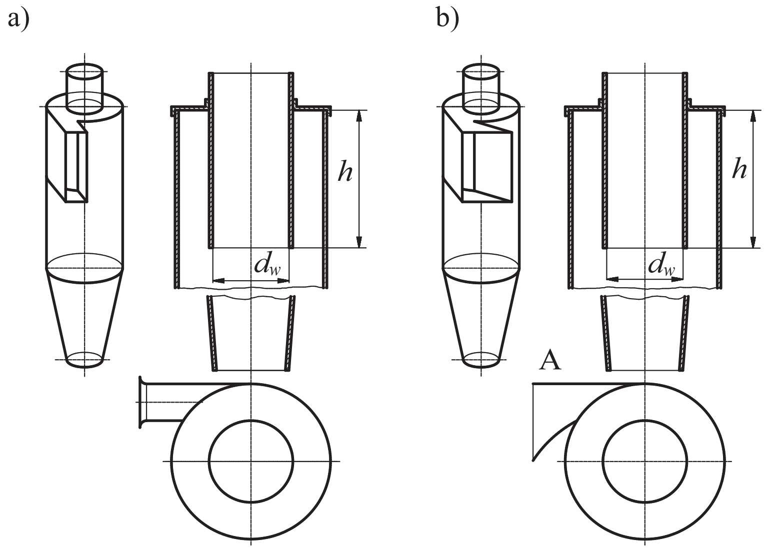

Fig. 8. Modified D-40 type mini-cyclone design: a) original (symmetrical) inlet port, b) asymmetrical curvilinear inlet

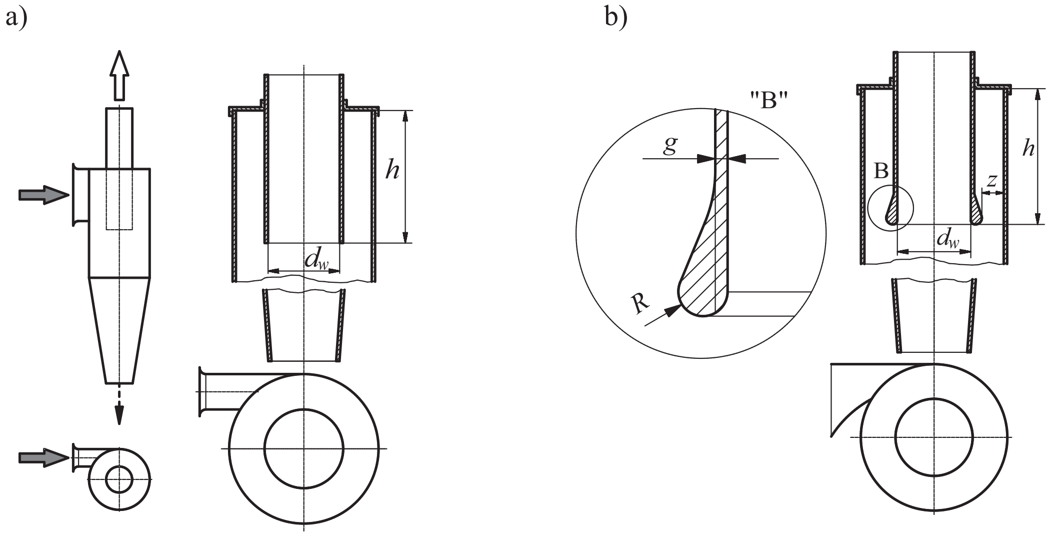

Fig. 9. type mini-cyclone: a) cylindrical outlet vortex finder – original version, b) cylindrical outlet vortex finder with streamlined inlet port

The existing cylindrical outlet vortex finder with internal diameter d_w was replaced with a truncated cone-shaped vortex finder, with a smaller diameter equal to the inner diameter of the outlet vortex finder $d_w = 23$ mm. A conical outlet vortex finder is a diffuser with an angle of flare $\alpha_s = 7°C$. For the angle value, the stream does not separate from the wall, no vortices are formed, and according to research (Bukowski, 1968) the coefficient of flow resistance ξ reaches the minimum.

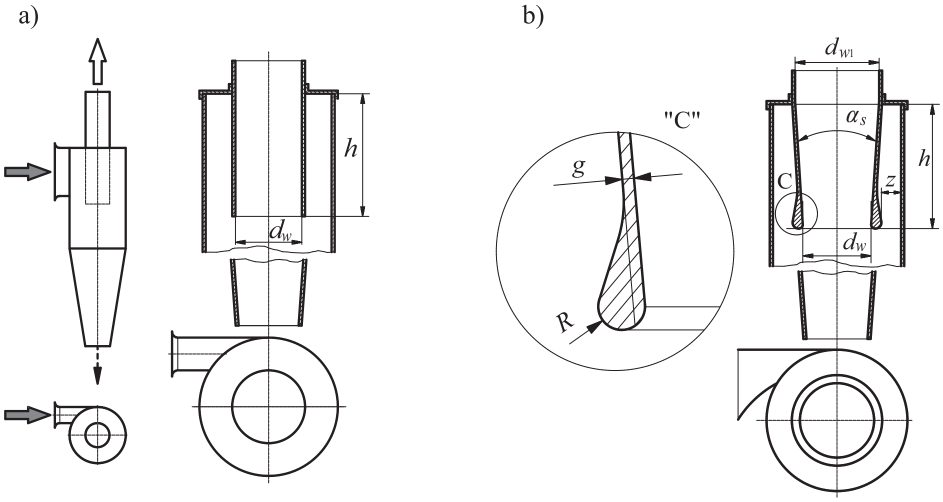

Fig. 10. D-40 type mini-cyclone: a) cylindrical outlet vortex finder – original version, b) conical outlet vortex finder with streamlined inlet port

4. TEST METHODS AND CONDITIONS

Mini-cyclone tests were performed on a special test stand (Fig. 11) for testing characteristics of separation efficiency $\varphi_c = f(Q_G)$, flow resistance $\Delta p_c = f(Q_{Gc})$ for air flow rate < 85 m^3/h (0.0305 kg/s) at ejector suction rate $< 20\%$ and dust concentration < 3 g/m^3.

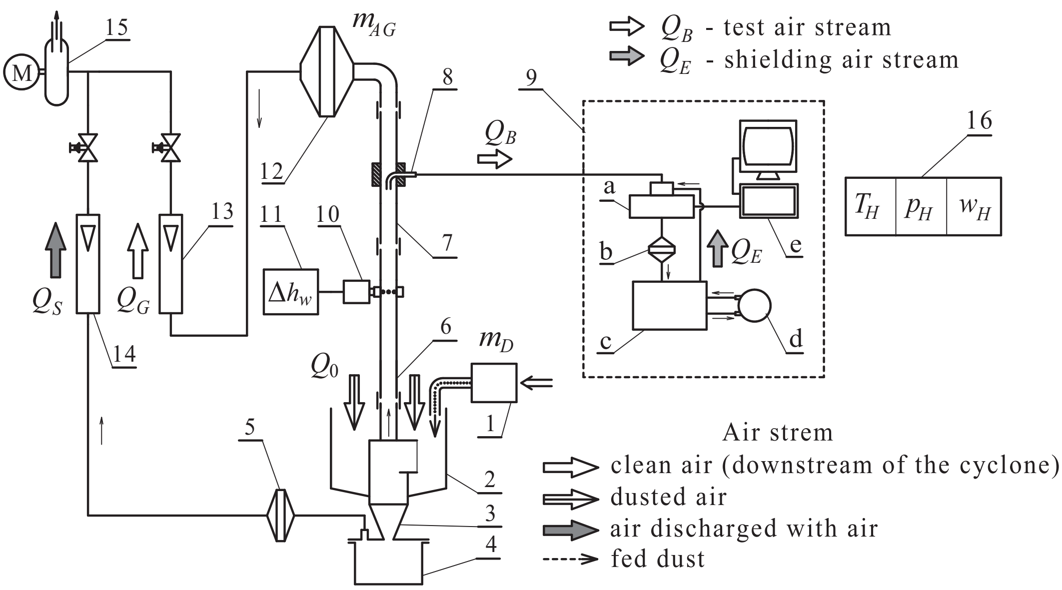

Fig. 11. Mini-cyclone test stand diagram: 1 – mini-cyclone, 2 – dust collector, 3 – dust chamber, 4 – dust feeder, 5 – absolute rated filter, dust suction line, 6 – mini-cyclone flow resistance measuring line, 7 – CL1A pressure sensor, 8 – pressure transducer and CL 134/24V control panel, 9 – measuring line with particle counter probe (a – sensor, b – filter air, c – block of the flow control, d – pump, e – computer), 10 – measuring probe, 11 – particle counter, 12 – absolute rated filter, main line, 13, 14 – main and suction stream measuring rotameters, 15 – suction fan, 16 – pressure, temperature and relative humidity measuring unit

The test stand included a particle counter Pamas-2132 with sensor HCB-LD-2A-2000-1 to determine number and size of dust particles in the air stream downstream of the mini-cyclone ranging from 0.7 to 100 μm, in $i = 32$ ranges limited with diameters $(d_{zimin} - d_{zimax})$. The range widths of measured size distribution are freely programmable. The maximum particle count for precise measurement (to avoid coincidence) is limited to 1000/ml, corresponding to a mass dust concentration $s \approx 0.25$ g/m^3.

Downstream the test equipment the purified air stream passes through an absolute filter, which protects the rotameter against dust ingress, and at the same time it enables to determine collected dust mass m_{AG} penetrating through the mini-cyclone and as a result determine mini-cyclone separation efficiency φ_c. Mini-cyclone tests were performed for the air stream $Q_{Gmin} - Q_{Gmax}$ resulting from the number of mini-cyclones used in T-72 tank air filter's multi-cyclone and air demand ranging from Q_{Gc} =1200–3400 m^3/h (0.42–1.21 kg/s) in the tank engine speed range $n_{\min} - n_N$.

The duration of a single measurement (time of uniform feeding and distribution of test dust at dust concentration $s = 1$ g/m^3) was $t_{\exp} = 3$ min. PTC-D test dust, a substitute for AC-fine test dust was used. Size distribution and chemical composition of the PTC-D dust is presented in Fig. 12.

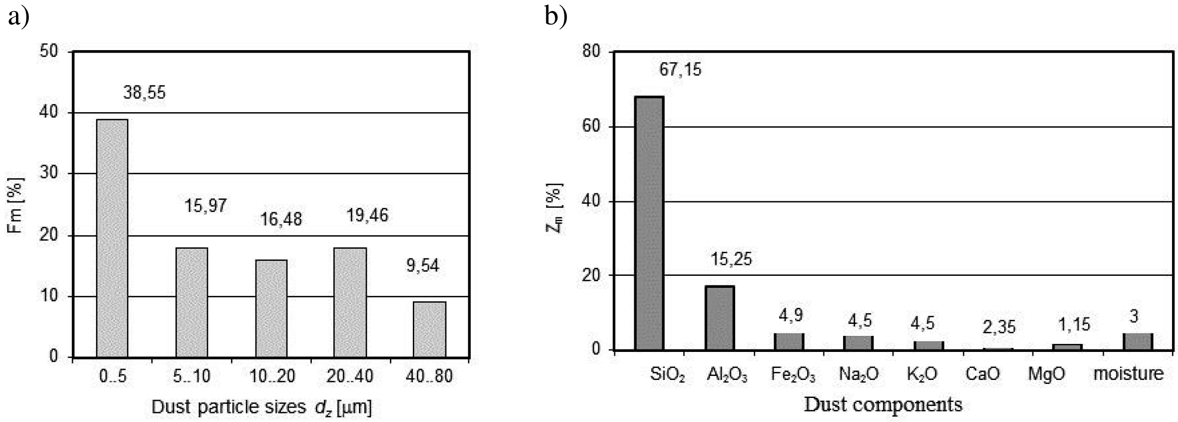

Fig. 12. PTC-D test dust used for testing: a) size distribution, b) chemical composition (PN-S- 34040, 1996)

The separation efficiency φ_c of the mini-cyclone was determined using a gravimetric method for predefined air flow rate $Q_{Gc} = 6$–34 m^3/h (every 4 m^3/h) and corresponding flow rate of air discharged through the bottom with dust particles Q_S was 8% of the total outlet flow Q_{Gc}.

A number of j =5 measurements was performed for each measuring point $p = I, II, III \ldots k$, starting at $Q_{Gc} = 6$ m^3/h, and separation efficiency φ_{cj} of the mini-cyclone was calculated for each measurement from the following relation:

$$\varphi_{cj} = \frac{m_{Zcj}}{m_{Dcj}} \cdot 100\% \tag{2}$$

Mass of dust fed to the cyclone was determined after each measurement from the following relation:

$$m_{Dcj} = m'_{Dcj} - m''_{Dcj} \tag{3}$$

Mass of dust retained by the mini-cyclone was determined after each measurement from the following relation:

$$m_{Zcj} = m_{Dcj} - m_{AGj} \tag{4}$$

Mass m_{AGj} of dust retained by absolute rated filter on the main line determined from the following relation:

$$m_{AGj} = m''_{AGj} - m'_{AGj} \tag{5}$$

In the distance $6d_w$ from the face surface of the mini-cyclone body (where d_w internal diameter of the mini-cyclone outlet line) the static pressure drop Δh_{wj} in mm H_2O was read out on the pressure transducer panel, and the value of mini-cyclone flow resistance Δp_c was determined from the following relation:

$$\Delta p_{cj} = \frac{\Delta h_{wj}}{1000}(\rho_m - \rho_H)g \tag{6}$$

The air dust concentration in time for all measurements was calculated from the following relation:

$$s_j = \frac{m_{Dcj}}{Q_{0cj} \cdot t_{\exp}} = \frac{m_{Dcj}}{(Q_{Gcj} + Q_{Scj}) \cdot t_{\exp}} \tag{7}$$

After the cycle of $j = 5$ measurements in a point p, the mean values of separation efficiency, flow resistance and dust concentration were calculated.

During the measurement ($t_p = 1/2\ t_{\exp}$ time), the number and size of dust particles in air downstream of the mini-cyclone was determined using a particle counter. The Up_i fraction of dust particles for each measuring range $(d_{zimin} - d_{zimax})$ in the total number of dust particles for all measuring ranges i was calculated:

$$Up_i = \frac{N_i}{\sum_{i=1}^{32} N_i} \tag{8}$$

The experimental tests also included determination of characteristics of separation efficiency $\varphi_c = f(Q_{Gc})$ and flow resistance $\Delta p_c = f(Q_{Gc})$ and separation performance (measurement of number and size of dust particles in the air stream Q_{Gc}) of D-40 type mini-cyclone: in original version – stage I and modified version – stage II.

5. TEST RESULT ANALYSIS

The characteristics of separation efficiency $\varphi_c = f(Q_{Gc})$ (Fig. 13a) of D-40 type mini-cyclone in original version have a similar course and conform to the information presented by the authors of many research studies and other authors' research studies (Dziubak 2000, Dziubak 2004, Dziubak 2006). With the increase in air stream value $Q_{Gc} = 6-18$ m^3/h (corresponding to the average flow velocity at the outlet $\upsilon_w = 4-12$ m/s), the separation efficiency φ_c of the tested mini-cyclone increases rapidly.

Mini-cyclone flow velocity (average) outlet υ_w was determined from the following relation:

$$\upsilon_w = \frac{Q_{Gc}}{3600 \cdot A_w}\ [\mathrm{m/s}] \tag{9}$$

Further increase of air stream Q_{Gc} results in a slight increase in separation efficiency φ_c, whereas a slight decrease is observed in the final mini-cyclone operation phase. Maximum mini-cyclone separation efficiency $\varphi_{cmax} \cong 96.2\%$ is achieved for the air stream value $Q_{Gc} = 22-26$ m^3/h. The course of separation efficiency $\varphi_c = f(Q_{Gc})$ change is mainly caused by the interrelations between inertia forces P_d acting on a dust particle and aerodynamic forces P_R of the gas stream. With the increase in air stream flowing through the mini-cyclone (flow rate) the values of both forces increase, whereas at higher air stream values (above $Q_{GC} = 18$ m^3/h for the tested mini-cyclone) the increase in aerodynamic force P_R is higher than the increase in inertia force P_d, which impedes particle movement and may result in secondary capture by the outlet air stream from the mini-cyclone. The mini-cyclone separation efficiency is reduced as a result.

Fig. 13b shows a relation between the separation efficiency φ_c and the dust particle size d_{zmax} in the air downstream of D-40 type mini-cyclone in its original version. The increase in air stream (flow rate) $Q_{Gc} = 6-22$ m^3/h results in dust particles with continuously decreasing dimensions downstream of the mini-cyclone, which explains the increase in mini-cyclone separation efficiency φ_c within this range.

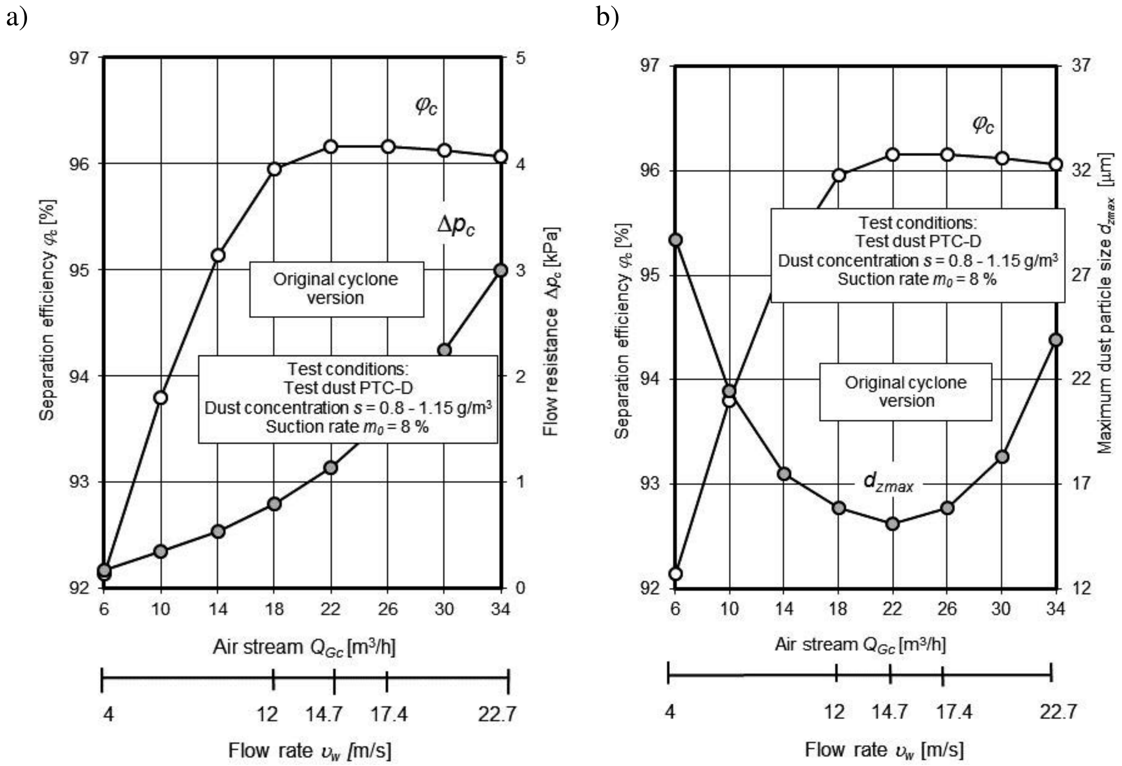

Fig. 13. D-40 type mini-cyclone characteristics – original version: a) separation efficiency $\varphi_c = f(Q_{Gc})$ and flow resistance $\Delta p_c = f(Q_{Gc})$, b) dust particle sizes $d_{zmax} = f(Q_{Gc})$

For air stream $Q_{Gc} = 6$ m^3/h, the values of maximum dust particle sizes d_{zmax} are the highest within the range of $d_{zmax} = 27.1-28.7$ μm, and for $Q_{Gc} = 22$ m^3/h the values are the lowest within the range of $d_{zmax} = 13.5-15.1$ μm. With the further increase in flow rate in the mini-cyclone, the effect of an increase in maximum dust particle size d_{zmax} is observed in the outlet air stream with a slight decrease in separation efficiency φ_c. Air particles with a maximum size of $d_{zmax} = 23.9$ μm are present in the air stream at $Q_{Gc} = 34$ m^3/h.

Irrespective of the stream Q_{Gc} value, the number of dust particles in the air downstream of the mini-cyclone (with the increase in size) is reduced until total elimination. The dust particle fraction Up from each measuring range Δd_z decreases continuously – Fig. 14. In the last measuring range, a single dust particle is usually present ($d_z = d_{zmax}$ size). Similar test results were obtained by Jo et al., (2000), testing a reverse flow mini-cyclone with a tangential inlet with $D = 31.1$ mm diameter at air stream $Q_{Gc} = 30.24-66.24$ m^3/h with test dust density of $\rho_{zp} = 0.98$ g/cm^3.

Large dust particles in the air downstream of the mini-cyclone at higher air stream values may be caused by the dust particles hitting a mini-cyclone wall at high speed bouncing from the wall, captured by the air stream and discharged to the mini-cyclone outlet (Dzierżanowski et al., 1985; Szczeciński, 2009). Those are single particles with large size and weight. The dust particle with the largest size $d_z = d_{zmax}$ in the air downstream of the mini-cyclone is taken as an assessment criteria for mini-cyclone air separation efficiency.

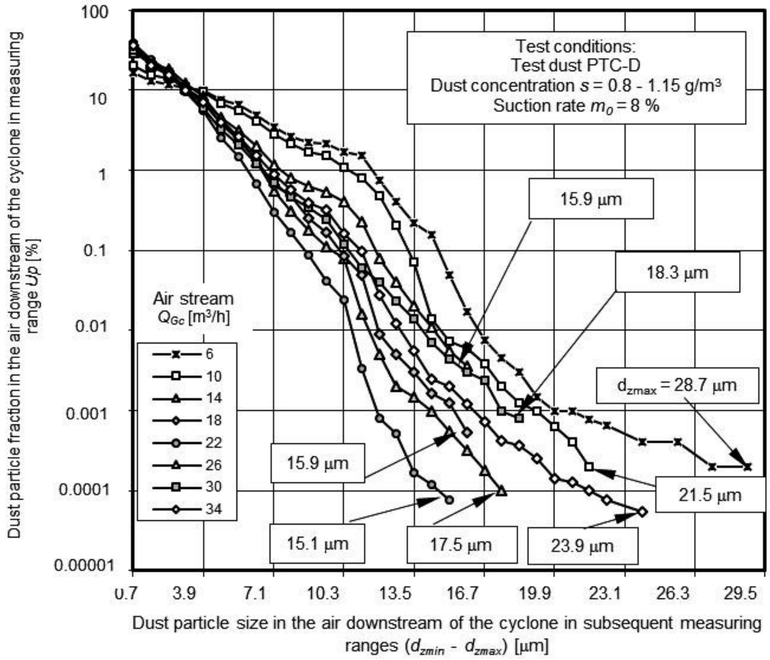

Fig. 14. Fraction of dust particles in the air downstream of D-40 type mini-cyclone for various air stream Q_{Gc} values

Theoretically, in the air downstream of the mini-cyclone at steady flow conditions (constant Q_{Gc} stream value), only dust particles below a specific limiting size d_{zg}, should be present, with a value determined from the relation specified by Dziubak (2012) and modified by the author:

$$d_{zg} = \frac{3}{2}\sqrt{\frac{A_0}{A_w}\frac{D}{\upsilon_0}\left(\frac{D}{d_w}\right)^{-(2m+1)}\left(\frac{h_w}{d_w}\right)^{-1}\frac{\mu_g}{\rho_{zp}}} \tag{10}$$

Mini-cyclone inlet flow velocity (average) υ_0 was determined from the following relation:

$$\upsilon_0 = \frac{Q_0}{3600 \cdot A_0}\ [\text{m/s}] \tag{11}$$

Table 1 shows the maximum size of particles d_{zgr} as calculated from Equation (6) of main dust components (SiO_2, Al_2O_3, Fe_2O_3) for the tested mini-cyclone.

Table 1. Dust particle boundary size d_{zgr} calculation results

Q_{Gc} [m^3/h]	υ_0 [m/s]	d_{zgr} [μm]		
		SiO_2 $\rho_{zp} = 2.65$ g/cm^3	Al_2O_3 $\rho_{zp} = 3.99$ g/cm^3	Fe_2O_3 $\rho_{zp} = 5.24$ g/cm^3
6	5.65	2.23	1.85	1.59
22	20.6	1.16	0.96	0.84
34	31.8	0.94	0.79	0.68

Calculated d_{zgr} sizes differ from one another and have very low values (2.23–0.68 μm), significantly lower than the dust particle sizes d_{zmax} present in the air downstream of the tested mini-cyclone. With the increase in air stream Q_{Gc} flowing through the mini-cyclone and dust particle density, sizes d_{zgr} continuously decrease, corresponding to the general theory of mini-cyclone operation.

There is no visible boundary (boundary particle size d_{zgr}), above which all dust particles will be retained by the mini-cyclone. The PTC-D test dust used for tests, corresponding to the road dust is a polydispersed dust with variable chemical composition. Dust particles are characterized by a different size (up to $d_z = 80\ \mu$m), variable shape (other than spherical) and density (Table 1). The dust particles of the same size (and the same volume) have various weight affecting inertia force. An adverse P_R and P_d force relation includes low weight and high volume (low density) dust particles. Assuming lack of the effect of particle shape on medium resisting force P_R the particles with higher density, e.g. iron oxides or corundum will be separated with higher efficiency.

Figure 15 shows the separation efficiency, separation performance and flow resistance characteristics for the mini-cyclone in the original and the modified versions.

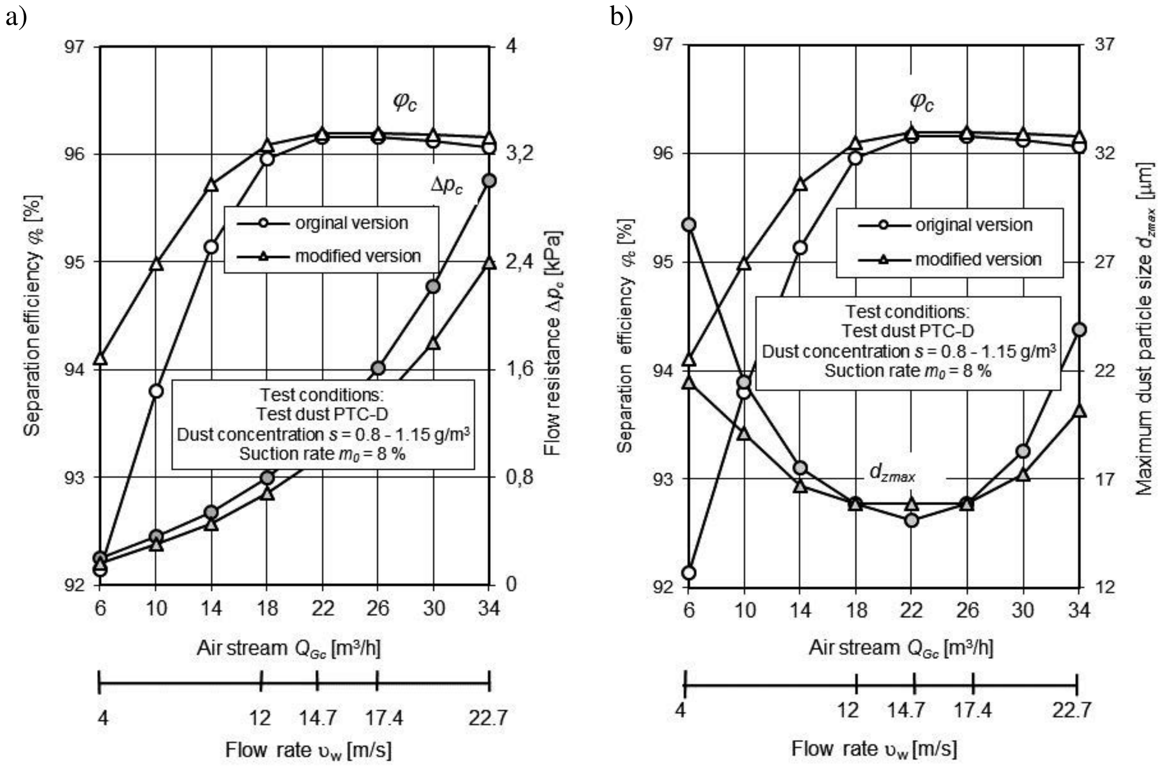

Fig. 15. Mini cyclone characteristics – original and modified versions: a) separation efficiency $\varphi_c = f(Q_{Gc})$ and flow resistance $\Delta p_c = f(Q_{Gc})$, b) separation efficiency $\varphi_c = f(Q_{Gc})$ and maximum dust particle size $d_{zmax} = f(Q_{Gc})$

The separation efficiency increase was achieved mainly within the range of small air stream values with an asymmetrical inlet providing the dust particle distribution with general dust mass accumulated on the external wall of a cylindrical section of the mini-cyclone. The movement of dust particles in the wall direction results in an increase in dust concentration near the walls. As a result of particle collisions near the walls, dust may aggregate and increase the effect of body forces and accelerate release of dust particles (in particular low size particles). The increase in mini-cyclone separation efficiency may have also been caused by an increase in aerosol flow rate in the throat "z" (Fig. 9b) caused by the streamlined ring at the outer surface of an outlet vortex finder. As a result, the dust particles with smaller sizes and lower weight achieved the velocity and the inertia force required for separation from the air.

A significant, approx. 30% reduction of mini-cyclone flow resistance, in relation to the results obtained for the original version, results from the decrease ($\upsilon_w = 22.7$ m/s to $\upsilon_w = 14$ m/s for $Q_{Gc} = 34$ m^3/h) in average outlet velocity υ_w caused by replacing a cylindrical outlet vortex finder with a conical outlet vortex finder.

The modification resulted in the increase in mini-cyclone separation efficiency, observed as a reduction in maximum dust particle size d_{zmax} fraction in the air downstream of the mini-cyclone within minimum and maximum values of the air stream Q_{Gc} flowing through the mini-cyclone.

Based on data presented in Figs. 13 to 15, the D-40 type mini-cyclone should operate within a wide range of air stream fluctuations $Q_{Gc} = 18-26$ m^3/h resulting from the maximum separation performance and minimum size dust particle concentration. A wider range would bring about a decrease of mini-cyclone efficiency and reduced separation performance, which would lead to a mass of dust being retained at the second filtration stage, and thus accelerated increase in flow resistance.

6. CONCLUSIONS

- Although there are several modifications available to improve a cyclone performance, not all solutions may be used in mini-cyclones utilized in the inlet air filtration systems of motor vehicles due to their complex design. An improved separation efficiency or a reduced flow resistance may be disproportionately low compared to the modification costs.
- For modification of mini-cyclones used in multi-cyclones of motor vehicle air filters, the following solutions may be used: modification of inlet port shape – replacing a symmetrical inlet with an asymmetrical inlet, modification of outlet duct (outlet vortex finder) shape from cylindrical to conical, streamlined outlet duct's inlet port shape or using cone in a dust discharge port.
- The separation efficiency of tested mini-cyclones (reverse flow cyclone with a tangential inlet in relation to a polydisperse dust with particle size up to d_z increases with the increase in flow rate υ (air stream Q_{Gc}) up to $\varphi_{cmax} \approx 96.2\%$, and is slightly reduced with further flow rate increase – Fig. 13. The course characteristics $\varphi_c = f(\upsilon)$ and efficiency values correspond to the data available in the literature presented by the authors of research studies (Hoffmann et al., 1991; Juda, 1968; Kabsch, 1992; Warych, 1998), and other author's research results (Dziubak, 2010, Dziubak, 1995).
- For specific flow conditions (Q_{Gc}), the number of dust particles in the air downstream of the mini-cyclone is systematically reduced with the increase in size and continues until total elimination – Fig. 14. In the last measuring range, a single dust particle is usually present ($d_z = d_{zmax}$ maximum size). There is no visible difference (at the boundary particle size d_{zgr}) between the dust particles retained by the mini-cyclone and discharged from the mini-cyclone with air. It is caused by the dust polydispersity, chemical properties and particle shape.
- For the air stream corresponding to the maximum separation efficiency φ_{cmax}, the maximum size of the dust particles in the air downstream the mini-cyclone (not separated in the mini-cyclone) achieves the lowest values within the range of $d_{zmax} = 13.5-15.1$ μm – Fig. 15, indicating an optimum range of the average outlet velocity υ_w for the mini-cyclone.
- The modified mini-cyclone design does not significantly affect changes in φ_c and Δp_c characteristics. The effect of design modification is a significant 30% reduction of flow resistance within the entire range of air stream Q_{Gc} and approx. 2% increase in separation performance φ_c within the range of the lowest air stream Q_{Gc} values and significant reduction of maximum dust particle d_{zmax} at extreme ($Q_{Gc} = 6$ m^3/h and $Q_{Gc} = 34$ m^3/h) air stream values – Fig. 15.

SYMBOLS

A	cross-section area, m^2
D	cyclone diameter, m

d_w outlet vortex finder diameter, m
H cyclone height, m
h_w outlet height, m
m equation exponent, 0.5–0.9
m_{Zc} mass of dust retained by mini-cyclone, kg
m_{Dc} mass of dust fed to cyclone in time t_{exp}, kg
m_{AG} mass of dust retained by absolute rated filter on the main line determined, kg
m'_{AGj} weight of absolute rated filter element before the measurement, kg
m''_{AGj} weight of absolute rated filter element after the measurement, kg
m'_{Dcj} dust feeder container weight before the measurement, kg
m''_{Dcj} dust feeder container weight after the measurement, kg
s dust concentration, g/m^3
t_{exp} time of uniform dust mass m_{Dj} feeding to the inlet air stream of the mini-cyclone Q_{0c}, s
Q volumetric flow rate, m^3/s

Greek symbols

Δp_c air flow resistance upstream of mini-cyclone, Pa
μ_g dynamic gas viscosity, kg/m s
ρ_a air density, kg/m^3
ρ_{zp} dust particle density, g/cm^3
ξ the coefficient of flow resistance
υ_w minicyclone outlet velocity, m/s
υ_0 minicyclone inlet velocity, m/s

Subscripts

a air
c cyclone
D intake
G main
H environmental conditions
i, j range, measuring cycle
k contraction
m manometric liquid
N the number of grains
p measuring point
R aerodynamic forces
S, s ejecting suction, cone
w inlet
Z dust retained
0 average value

REFERENCES

Azadi M., Azadi M., 2012. An analytical study of the effect of inlet velocity on the cyclone performance using mathematical models. *Powder Technol.*, 217, 121–127. DOI: 10.1016/j.powtec.2011.10.017.

Baczewski K., Hebda M., 1991/92. *Filtracja płynów eksploatacyjnych*. Radom, MCNEMT (in Polish).

Bernardo S., Mori M., Peres A.P., Dionısio R.P., 2006. 3-D computational fluid dynamics for gas and gas-particle flows in a cyclone with different inlet section angles. *Powder Technol.*, 162, 190–200. DOI: 10.1016/j.powtec.2005.11.007.

Bukowski J., 1968. *Mechanika płynów*. Warszawa, PWN (in Polish).

Cenrtisep Air Cleaner. 2004. PALL Corporation, USA.

Chu K.W., Wang B., Xu D.L., Chen Y.X., Yu A.B., 2011. CFD–DEM simulation of the gas–solid flow in a cyclone separator. *Chem. Eng. Sci.*, 66, 834–847. DOI: 10.1016/j.ces.2010.11.026.

Cortés C., Gil A., 2007. Modeling the gas and particle flow inside cyclone separators. *Prog. Energy Combust. Sci.*, 33, 409–452. DOI: 10.1016/j.pecs.2007.02.001.

Durst M., Klein G., Moser N., 2005. *Filtration in Fahrzeugen*. Ludwigsburg, Deutschland.

Dzierżanowski P., Kordziński W., Otyś J., Szczeciński S., Wiatrek R., 1985. *Napędy lotnicze. Turbinowe silniki śmigłowe i śmigłowcowe*. Warszawa, Wydawnictwa Komunikacji i Łączności (in Polish).

Dziubak T., 2012. The assessment of the possibilities of improvement of the extraction evenness in multicyclone dedusters fitted in special vehicles. *Combustion Engines,* 4, 151, 34–42.

Dziubak T., 2009. The problems of the inlet air filtration in the special vehicles combustion engines. *III International Congress on Combustion Engines*, Opole 22-24.06.2009. *Combustion Engines*, 2009-SC1**,** 115–123.

Dziubak T., 2006. Modification of returnable cyclone with a tangent inlet construction. *Bulletin of the Military University of Technology*, LV, 2, 279–301.

Dziubak T., 2004. The experimental assessment of constructional changes of motor vehicle air filter. *Bulletin of the Military University of Technology*, LIII, 10, 121–138.

Dziubak T., 2000. The problems of the air filtration in the vehicle engines exploitated in large pollution conditions. *Zagadnienia Eksploatacji Maszyn*, 35 (4), 181–197 (in Polish).

Dziubak T., 1995. Experimental investigation of returnable minicyclone with tangential inlet. *Bulletin of the Military University of Technology*, XLIV, 3/4, 113–125.

Hoffmann A.C., Arends H., Sie H., 1991. An experimental investigation elucidating the nature of the effect of solids loading on cyclone performance. *Filtr. Sep.*, 28, 188-193. DOI: 10.1016/0015-1882(91)80074-F.

Honeywell International Inc., 2000. AGT1500 Turbine Technology, Honeywell International Inc., USA. Available at: www.honeywell.com.

Jiao J., Zheng Y., Sun G., Wang J., 2006. Study of the separation efficiency and the flow field of a dynamic cyclone. *Sep. Purif. Technol.*, 49, 157–166. DOI: 10.1016/j.seppur.2005.09.011.

Jo Y., Tien Ch., Ray M.B., 2000. Development of a post cyclone to improve the efficiency of reverse flow cyclones. *Powder Technol.*, 113, 97-108. DOI: 10.1016/S0032-5910(00)00206-0.

Juda J., 1968. *Pomiary zapylenia i technika odpylania*. Warszawa, WNT (in Polish).

Jung Ch.H., Xiang R.B., Kim M.C., Lim K.S., Lee K.W., 2004. Performance evaluation of a cyclone with granular packed beds. *J. Aerosol Sci.*, 35, 1483–1496. DOI: 10.1016/j.jaerosci.2004.06.076.

Kabsch P., 1992. *Odpylanie i odpylacze*. Warszawa, WNT (in Polish).

Karagoz I., Avci A., Surmen A., Sendogan O., 2013. Design and performance valuation of a new cyclone separator. *J. Aerosol Sci.*, 59, 57–64. DOI: 10.1016/j.jaerosci.2013.01.010.

Kobyłecki R., 2011. Unburned carbon in the circulating fluidised bed boiler fly ash. *Chem. Process Eng.*, 32, 255–266. DOI: 10.2478/v10176-011-0020-8.

Krasiński A., 2007. Estimation of operation parameters of cyclones based on the CFD simulations. *Chem. Process Eng.*, 28, 4, 961–972.

Lim K.S., Kim H.S., Lee K.W., 2004. Characteristics of the collection efficiency for a cyclone with different tube shapes. *J. Aerosol Sci.*, 35, 743–754. DOI: 10.1016/j.jaerosci.2003.12.002.

Lim K.S., Kwon S.B., Lee K.W., 2003 Characteristics of the collection efficiency for a double cyclone with clean air inlet. *J. Aerosol Sci.*, 34, 1085–1095. DOI: 10.1016/S0021-8502(03)00079-X.

Liu Z., Zheng Y., Jia L., Jiao J., Zhang O., 2006. Stereoscopic PIV studies on the swirling flow structure in a gas cyclone. *Chem. Eng. Sci.*, 61, 4252–4261. DOI: 10.1016/j.ces.2006.01.024.

Ma L., Ingham D.B., Wen X,. 2000. Numerical modelling of the fluid and particle penetration through small sampling cyclones. *J. Aerosol Sci.*, 31, 1097–1119. DOI: 10.1016/S0021-8502(00)00016-1.

PN-S-34040, *Silniki spalinowe. Filtry powietrza. Wymagania i badania*. PKN, 1996.

Sakura G.B., Leung A.Y.T., 2015. CFD simulation of cyclone separators to reduce air pollution. *Powder Technol.*, 286, 488–506. DOI: 10.1016/j.powtec.2015.08.023.

Swift P., 1986. An empirical approach to cyclone design and application. *Filtr. Sep.*, 23, 1, 24–27.

Szczeciński S., 2009. The problems of filtration of inlet air for turbine helicopter engines. *Trans. Aviation Institute*, 199, 25–30.

Wang B., Xu D.L., Chu K.W., Yu A.B., 2006. Numerical study of gas–solid flow in a cyclone separator. *Appl. Math. Modell.*, 30, 1326–1342. DOI: 10.1016/j.apm.2006.03.011.

Wasilewski M., Duda J., 2016. Multicriteria optimisation of first-stage cyclones in the clinker burning system by means of numerical modelling and experimental research. *Powder Technol.*, 289, 143–158. DOI: 10.1016/ j.powtec. 2015.11.018.

Warych J., 1998. *Oczyszczanie gazów – procesy i aparatura*. Warszawa, WNT (in Polish).

Winfield D., Cross M., Croft N., Paddison D., Craig I., 2013. Performance comparison of a single and triple tangential inlet gas separation cyclone: A CFD study. *Powder Technol.*, 235, 520–531. DOI: 10.1016/j.powtec. 2012.10.026.

Qian F., Zhang J., Zhang M., 2006. Effects of the prolonged vertical tube on the separation performance of a cyclone. *J. Hazard. Mater.*, 136, 822–829. DOI: 10.1016/j.jhazmat.2006.01.028

Yoshida H., Ono K., Fukui K., 2005. The effect of a new method of fluid flow control on submicron particle classification in gas-cyclones. *Powder Technol.*, 149, 139–147. DOI: 10.1016/j.powtec.2004.10.005

Zhao B., Shen H., Kang Y., 2004. Development of a symmetrical spiral inlet to improve cyclone separator performance. *Powder Technol.*, 145, 47–50. DOI: 10.1016/j.powtec.2004.06.001.

Zhu Y., Kim M.C., Lee K.W., Park Y.O., Kuhlman M.R., 2001. Design and performance evaluation of a novel double cyclone. *Aerosol Sci. Technol.*, 34, 373–380. DOI: 10.1080/02786820120723.

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