

EXAMINING OF THE EFFECTIVENESS OF OPERATION OF A SYSTEM TO REDUCE PARTICULATE MATTER EMISSION FROM MOTOR VEHICLE BRAKE MECHANISMS IN CONDITIONS SIMULATING THE REAL VEHICLE USE

ANNA KIERACIŃSKA¹, JACEK BIEDRZYCKI², ZDZISŁAW CHŁOPEK³, ANDRZEJ JAKUBOWSKI⁴,
JAKUB LASOCKI⁵, PIOTR WÓJCIK⁶

Automotive Industry Institute (PIMOT), Warsaw University of Technology

Summary

The devices to reduce particulate matter emission from disc brake and drum brake mechanisms of motor vehicles successfully passed rig tests carried out on laboratory test stands. In this paper, results of testing the devices installed in a passenger car have been presented. The tests were carried out on a vehicle chassis dynamometer in the conditions of special driving tests. The effectiveness of operation of the system under consideration was found to be good: the particulate matter emission was reduced by about 50 to 70%. The examinations have revealed that the brake dusts comprise particles of very small dimensions and that heavy metals are among the major particle components. Results of tests carried out when the test vehicle was driven in real urban traffic confirmed high effectiveness of operation of the system developed. However, the road test results were not as good as the results obtained from the chassis dynamometer tests because of some design problems that emerged at the installation of an autonomous system version in the test vehicle. The experience gained at the road tests is now used for modifying the system to reduce dust emission from motor vehicle brake mechanisms.

Keywords: exhaust emissions, particulate matter emission, braking systems, motor vehicles

1. Introduction

Among many factors causing environmental hazards, whether of natural or anthropogenic origin, dust is one of those being most dangerous [1, 3, 10, 13, 14, 17, 19, 24, 25]. Excessive

¹ Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warsaw, Poland, e-mail: a.kieracinska@pimot.eu, ph.: +48 22 777 70 73

² Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warsaw, Poland, e-mail: j.biedrzycki@pimot.eu, ph.: +48 22 777 71 91

³ Warsaw University of Technology, ul. Narbutta 84, 02-524 Warsaw, Poland, e-mail: zchlopek@simr.pw.edu.pl, ph.: +48 22 849 03 14

⁴ Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warsaw, Poland, e-mail: a.jakubowski@pimot.eu, ph.: +48 22 777 71 86

⁵ Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warsaw, Poland, e-mail: j.lasocki@pimot.eu, ph.: +48 22 777 71 91

⁶ Automotive Industry Institute, ul. Jagiellońska 55, 03-301 Warsaw, Poland, e-mail: p.wojcik@pimot.eu, ph.: +48 22 777 71 91

dust immission⁷ is the most frequently detected exceedance of the permissible limits of pollutant immissions in the atmospheric air [3, 13, 14, 19, 24, 25]. The harmful impact of dusts suspended in the atmospheric air on living organisms is commonly known. It was as long ago as in 1524 when Georgius Agricola wrote a study "De re metalica" [1], where information was provided about the harmful impact of dust on the human health.

The term "dust" is defined as the dispersed phase of a two-phase system consisting of solid body, i.e. small solid particles, suspended in gaseous dispersion medium, i.e. air [11, 12, 16]. In general, the shape of dust particles is not spherical. Therefore, a standardized method must be adopted by convention to evaluate the equivalent particle size. There are many criteria of defining the equivalent size of dust particles. Usually, the method of determining the equivalent particle size is defined by the relevant regulations [2, 4, 11, 12, 16, 17, 21–23].

Depending on the equivalent dust particle size, the following dust categories are defined [9, 10–12, 16, 17, 20, 22, 23]:

- TSP (total suspended particles), with equivalent particle size below 300 μm ;
- Fine-grained dust, consisting of particles of equivalent size below 75 μm , which settle out under their own weight but may remain suspended for some time;
- Fine dust PM₁₀, with equivalent particle size below 10 μm ;
- Fine dust PM_{2.5}, with equivalent particle size below 2.5 μm ;
- Dust PM₁, with equivalent particle size below 1 μm ;
- Nanoparticles⁸, with equivalent particle size below 100 nm [2, 20] (dust invisible to the naked eye).

The particulate matter fractions PM₁₀ and PM_{2.5} are defined in a special way. The particulate matter PM₁₀ is the dust that can go through a size-selective inlet as defined in the reference method for the sampling and measurement of PM₁₀ (see EN 12341) with a 50% efficiency cut-off at an aerodynamic diameter (AED) of the particles of up to 10 μm . The particulate matter PM_{2.5} is the dust that can go through a size-selective inlet as defined in the reference method for the sampling and measurement of PM_{2.5} (see EN 14907) with a 50% efficiency cut-off at an aerodynamic diameter (AED) of the particles of up to 2.5 μm . Similar definitions are applicable to other particle size fractions, e.g. PM₁.

From the point of view of the impact of dust on the human respiratory tract, a term "respirable dust" can also be met [22, 23]. The respirable dust is a set of the particles that can pass through a preliminary particle selector with size-permeability (based on equivalent particle sizes) described by a log-normal probability function with an average AED value of $3.5 \pm 0.3 \mu\text{m}$ and a standard deviation of $1.5 \pm 0.1 \mu\text{m}$ [22, 23].

According to standard EN 481 [16], two dust fractions are defined:

- Inhalable fraction (that can be breathed into the nose or mouth);
- Thoracic fraction (that can penetrate to the bronchioles).

⁷ „Immission” is the concentration of a pollutant dispersed in the atmospheric air, measured at a height of 1.5 m above the Earth's surface [18].

⁸ There are some differences in defining the term "nanoparticles". This is, to a significant extent, because of the spontaneous introduction of this idea both in the field of sciences and in non-scientific activities and due to a tendency observed for the recent years that commercial expressions are readily adopted by scientific circles to function as scientific terms. So, the values of 50 nm or even 1 μm can be met as the upper limit defining the equivalent size of nanoparticles [2, 20].

The inhalable fraction consists of particles with equivalent sizes smaller than 100 μm . Particles with dimensions bigger than 30 μm are arrested in the upper part of the respiratory tract (nose, mouth, throat, larynx) and then excreted with mucus. The middle parts of the respiratory tract (trachea, bronchi, bronchioles) are reached by the thoracic fraction, the particle size of which does not exceed 20 μm . These particles may accumulate in the upper and middle parts of the respiratory tract. The gas-exchange regions (alveoli) are reached by the particles whose dimensions are smaller than 7 μm . Such particles are the basic component of the respirable dust, which remains there for a quite long time causing pathological changes. The particles with dimensions smaller than 2.5 μm penetrate to, and accumulate in, the deepest lung regions. The dust particles soluble in body fluids penetrate directly into the blood.

The harmful impact of dust on the human and animal health depends on the size, chemical and mineralogical composition, and physical structure of dust particles [3, 4, 13, 14, 17, 19, 24, 25].

Fine dusts, especially particulate matter fraction PM_{2.5}, cause various respiratory diseases such as asthma or chronic bronchitis, lead to worsening of the function of lungs, and even can contribute to premature death. There are many publications univocally confirming that the air pollution with dusts is a factor aggravating the symptoms of chronic obstructive pulmonary disease (COPD) [19].

Particularly harmful to the human health are the dusts that contain particles with heavy metal compounds (especially arsenic, lead, cadmium, nickel, and mercury), as many of the components of such dusts have mutagenic or carcinogenic properties. The particles with heavy cyclic hydrocarbons, also counted among carcinogenic compounds, are extremely toxic, too.

Depending on particle size, dust particles penetrate into different regions of the human respiratory system (see Fig. 1).

The way how dusts affect the human health may be illustrated by the shares of dust deposition in different parts of the human respiratory system, in terms of particle diameters (Fig. 2).

Particulate matter may be of both natural and civilization (anthropogenic) origin [9, 10, 18, 20, 24]. The basic natural sources of dusts are sedimentary materials, marine, vegetable and animal aerosols and, above all, substances released to the atmosphere in result of volcano eruptions and forest fires [8, 9, 24]. The anthropogenic causes for the dust emission actually include all the civilization activities, especially production processes and the processes where the combustion of fuels (chiefly solid fuels) is involved, including the use of domestic fires. An important source of particulate matter emissions is also transport [7, 8].

The particulate matter emissions from motor transport predominantly come from the following sources [6, 9, 10]:

- Combustion engines, which emit particulate matter together with exhaust gases;
- Tribological pairs in the vehicles;

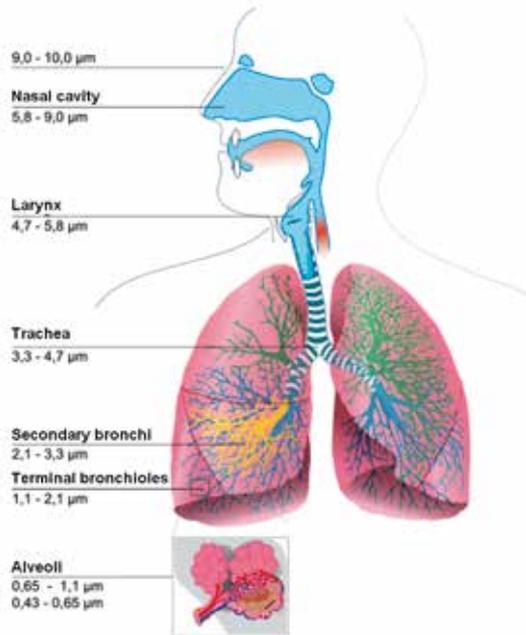


Fig. 1. Human respiratory system regions exposed to the penetration of specific particulate matter fractions [15]

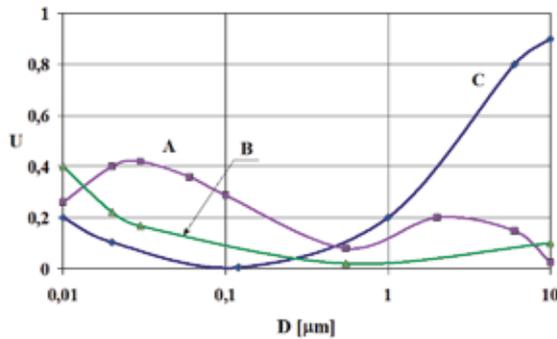


Fig. 2. Distribution of dust particle diameters D (shares of deposition, U) arrested in various parts of the human respiratory system (based on [24]):

A - lungs; B - trachea and bronchi; C - epipharynx

- Road wheel tyres and pavement material, rubbed off in result of the tyre-road interaction;
- Materials of other vehicle parts when undergoing wear processes;
- Material stirred up from the road surface by vehicles moving on the road.

The automotive dusts coming from sources other than combustion engines may have a significant share in the emission of particulate matter from transport-related sources.

The emission of dust fractions from sources other than combustion engines, especially in the case of heavy transport, may significantly exceed the emission of particulate matter contained in exhaust gases, according to estimates [3, 4]. Among the tribological pairs in a motor vehicle, a special role in the dust emissions is played by the braking system. The friction pairs in the braking system make an important source of dust emission in connection with the function fulfilled by the braking system and consisting in the dissipation of kinetic energy of the vehicle. An average motor vehicle annually consumes about 0.5 kg of friction material of its braking system, according to estimates [6, 7]. Additionally, it is known that the dusts emitted from brake mechanisms are very fine and contain substances particularly harmful to human and animal health.

In this connection, work to reduce particulate matter emission from brake mechanisms of motor vehicles was undertaken at the Automotive Industry Institute (PIMOT). Test systems to serve this purpose, intended for both disc brake and drum brake mechanisms, were designed, built, and subjected to laboratory tests carried out on special test rigs at PIMOT. The test results were very promising, especially for the system intended for disc brakes, where the coefficient of effectiveness of the reduction of dust emission from the braking system reached values of up to 0.8 [6, 7].

The task to develop and test the systems to reduce the particulate matter emission from brake mechanisms, in a version suitable for being installed in vehicles, was undertaken within National Research and Development Centre's development project No. 10 0050 10/2010 entitled "Development of systems to reduce dust emission from disc brake and drum brake mechanisms of motor vehicles," carried out at PIMOT. Some results of the tests carried out within this project have been presented herein.

2. Testing of a system to reduce particulate matter emission from brake mechanisms of a passenger car on a chassis dynamometer and in monitored service conditions

2.1. System to reduce particulate matter emission from brake mechanisms in the version as installed in the vehicle

The system to reduce particulate matter emission from brake mechanisms was installed in a Citroen Berlingo vehicle, manufactured in 2000, with a compression-ignition engine of 1 868 cm³ cubic capacity. The front and rear vehicle wheels were provided with disc and drum brakes, respectively.

To install the system under tests in the vehicle, the following parts of the original vehicle brake mechanisms were replaced:

- In the disc brakes: brake discs, brake calliper carriers, brake callipers, and brake pads;
- In the drum brakes: brake drums, brake shoes, and brake shoe adjuster springs.

The suction elements of the system to reduce dust emission from the disc brakes were mounted on appropriately shaped brackets bolted to the swivel axles at the places where

brake calliper carriers were originally fastened. Each suction nozzle was so positioned in relation to the brake disc that a 1 mm gap was left between the nozzle and the disc. The suction pads were connected by hoses 8 mm dia. to filters fixed on the ejectors. A disc brake of the Citroen Berlingo vehicle provided with the dust emission reduction system, prepared for testing, has been shown in Fig. 3.



Fig. 3. Disc brake of the Citroen Berlingo vehicle provided with the dust emission reduction system

For the suction elements to be installed in the drum brake mechanism, the brake shoes and backing plates were modified. For the sake of the best possible tightness between the suction pad surface and the inner surface of the brake drum, the gap between these surfaces was minimized by applying heat resistant silicone onto the suction pad edges. Two holes were drilled in each backing plate and metal pipes 8 mm dia. were put through the holes to the suction elements incorporated in the brake shoes. The pipes to extract dust from the two suction elements installed in one drum brake mechanism were connected together and the dust was carried away from them via a hose to one filter. All the process holes made to install the dust suction system were sealed with heat resistant silicone.

A drum brake mechanism provided with the dust emission reduction system has been shown in Fig. 4.

The following measuring transducers were installed in the vehicle for testing:

- Braking system pressure transducer ADZ Nagano SML with a measuring range from 0 to 25 MPa;
- Pneumatic system vacuum transducer ADZ Nagano SML with a measuring range from -0 to 0.3 MPa;
- Wheel rotational speed transducer;
- Brake disc and brake drum temperature transducers Optris CSmicro with a measuring range from -20 to 500 °C.



Fig. 4. Drum brake of the Citroen Berlingo vehicle provided with the dust emission reduction system (the red circles indicate the suction elements)

The transducers were wired to a central unit specially designed for this purpose, which was to record time histories of the quantities measured. For the purposes of ongoing verification of the selected parameters of operation of the braking system and the dust emission reduction system, the central unit made it possible to monitor their values on a display screen.

2.2. Examining of the effectiveness of operation of the system to reduce particulate matter emission from motor vehicle brake mechanisms

The effectiveness of operation of the system to reduce particulate matter emission from motor vehicle brake mechanisms was examined on a chassis dynamometer Schenk Komeg EMDY 48 with a system Horiba CRSD 7000, which assisted in performing the driving tests.

The vehicle movement was simulated in a special driving test, which ensured adequate braking intensity and repeatability of test conditions. The vehicle wheels were driven with a constant speed of 20 km/h by dynamometer rolls instead of the vehicle engine. The vehicle brakes were cyclically operated with constant frequency, with each of the cycles consisting of a brake application period of 5 s followed by a period of 10 s without braking. The test consisted of 240 single braking cycles in total; in consequence, the test duration time was 3 600 s and the distance travelled by the vehicle totalled 20 km. The share of the brake application time in the total test duration time was 0.33.

In the initial phase of each braking period, the vehicle speed decreased. Then, despite of the fact that a constant pressure was applied to the brake pedal, the vehicle speed returned to a level of about 20 km/h due to the operation of a dynamometer roll speed governor. When

the brake pedal was released, the vehicle speed rapidly rose and immediately after that, it was brought again to the level of 20 km/h by the governor.

A fragment of the special test aimed at examining the effectiveness of operation of the system to reduce dust emission from passenger car brake mechanisms has been illustrated in Fig. 5.

Time histories of the following quantities were recorded during the tests:

- Hydraulic pressure in the braking system;
- Vacuum in the pneumatic system;
- Vehicle speed;
- Temperature of the brake discs and brake drums.

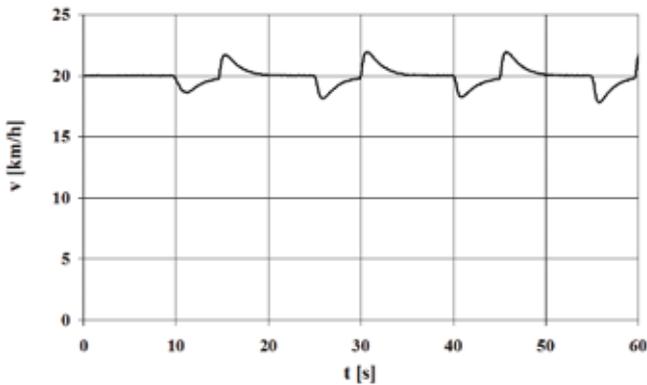


Fig. 5. Schematic diagram of the driving test aimed at examining the effectiveness of operation of the system to reduce particulate matter emission from passenger car brake mechanisms: v - vehicle speed

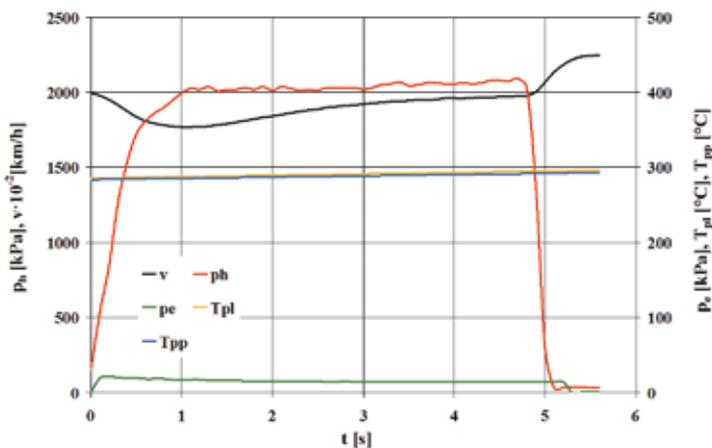


Fig. 6. Example time histories of vehicle speed (v), hydraulic pressure in the braking system (p_h), vacuum in the pneumatic system (p_v), and temperatures of the left and right brake discs (T_{pl} and T_{pp} , respectively), recorded during vehicle braking in a special driving test

Example time histories of the quantities recorded, obtained from one realization of the process of braking with the use of disc brakes, have been presented in Fig. 6. Similar curves were also obtained for drum brakes.

During the tests, six series of measurements were carried out for the disc and drum braking systems each; every series consisted of four braking cycles (single realizations of a special driving test).

The effectiveness of operation of a system to reduce particulate matter emission from motor vehicle brake mechanisms was evaluated on the grounds of a coefficient of reduction of particulate matter emission; this coefficient was defined by the following formula:

$$k_{PM} = 1 - \frac{m_k - m_f}{m_k}$$

where:

m_f – difference in the filter mass;

m_k – difference in the mass of the brake pads or the brake shoes served by the specific filter.

The values of the coefficient of reduction of particulate matter emission from the vehicle braking system, obtained from individual test series, as well as the average value and standard deviation of the set of values of this coefficient have been shown in Figs. 7 and 8.

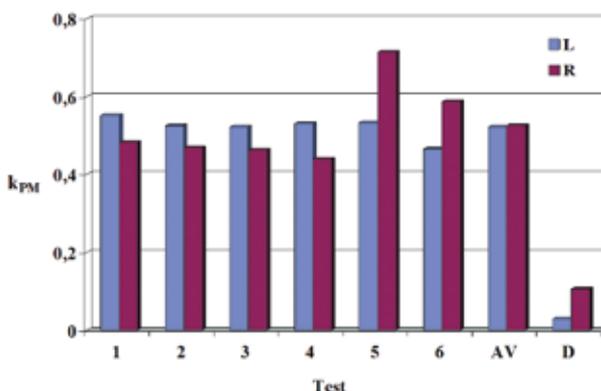


Fig. 7. Coefficient of reduction of particulate matter emission (k_{PM}) from disc brakes of the vehicle at individual test series:

AV – average value of the coefficient; D – standard deviation of the coefficient; L – left side of the vehicle; R – right side of the vehicle

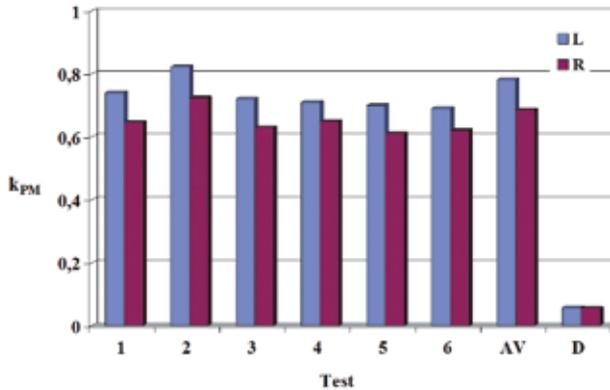


Fig. 8. Coefficient of reduction of particulate matter emission (k_{PM}) from drum brakes of the vehicle at individual test series:

**AV – average value of the coefficient; D – standard deviation of the coefficient;
L – left side of the vehicle; R – right side of the vehicle**

Afterwards, tests were carried out during vehicle operation in urban traffic conditions, characterized by high intensity of braking. These tests are still going on. The test results obtained until now have confirmed high effectiveness of operation of the system developed. However, these test results were not as good as those obtained from the tests carried out on a chassis dynamometer because of some design problems that emerged at the installation of the autonomous system version in the test vehicle. The experience gained at the road tests is now used for modifying the system to reduce dust emission from motor vehicle brake mechanisms.

2.3. Examining of the microstructure of dusts emitted from motor vehicle brake mechanisms

The microstructure of dusts emitted from motor vehicle brakes was examined on dust samples taken from disc brake and drum brake mechanisms.

The scope of this examination covered taking photos with the use of a metallographic microscope, analysing the microstructure of the samples, and determining the distribution of dimensions of the dust particles examined.

The microscopic specimens were made by embedding the samples in epoxy resin Epidian 5 with curing agent Z 1, grinding the specimen surfaces with abrasive paper of grit size from 100 to 800, and then polishing the surfaces with cotton cloth moistened with suspension of aluminium oxide of 0.1 μm grit size in demineralized water. The specimens subjected to examinations were either unetched or etched with the MiIFe agent to PN 61/H-04503, i.e. 5% nitric acid (HNO_3) solution in ethyl alcohol, used for the etching of iron alloys.

The specimens were examined with the use of a Neophot 2 metallographic microscope provided with camera, monitor, and thermal imaging printer. The microscope magnification was selected according to dimensions of the components of the structure of the objects examined; it ranged from $\times 76$ to $\times 2\ 600$.

The following has been obtained in result of the examinations:

- For the sample taken from the disc brakes, 20 photographs;
- For the sample taken from the drum brakes, 42 photographs.

The photographs were then processed, thanks to which histograms of particle dimensions could be determined for the dusts examined.

An example cross-section through dust agglomerates in the sample taken from the disc brakes (with white fields representing pores) has been presented in Fig. 9.



Fig. 9. Dust of the sample taken from the disc brakes; magnitude $\times 76$ (right) and $\times 910$ (left)

The dust agglomeration was found to result from the presence of electrostatic charges, which were generated due to friction between individual dust particles and between dust particles and internal walls of the plastic hoses feeding the dust from the suction pads to the filter. The dust agglomeration process could also be caused by high hygroscopicity of the dust.

From among many options, the conventional particle size has been assumed in this paper as the "surface area equivalent diameter," i.e. an equivalent diameter being equal to the diameter of a spherical particle with the same surface area as that of the particle under consideration [4, 21].

Fig. 10 shows the probability density of the equivalent diameter of dust particles in the sample taken from the disc brakes, i.e. the average values of the probability density for individual places of analysis (AV1–AV4) and the probability density value averaged for the sample as a whole (AV).

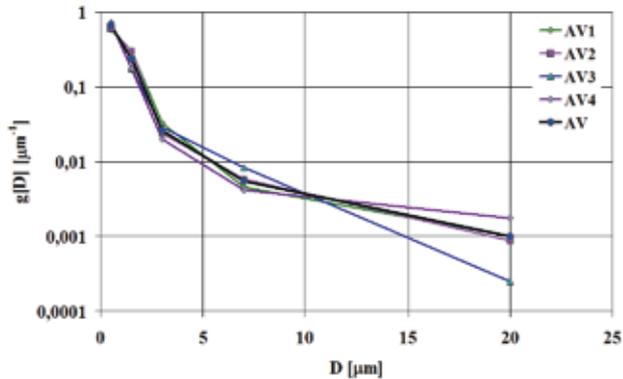


Fig. 10. Probability density of the equivalent diameter of dust particles in the sample taken from the disc brakes: the average values for individual places of analysis (AV1 through AV4) and the average value for the sample as a whole (AV)

Interestingly, only a small unrepeatability can be observed in the curves determined to represent the probability density of the equivalent dust particle diameter, both for individual analysed places in each of the samples and for the average values for the whole sample. This provides grounds for a statement that the results obtained may be considered reliable and honestly describing the observed properties of the dust samples under examination.

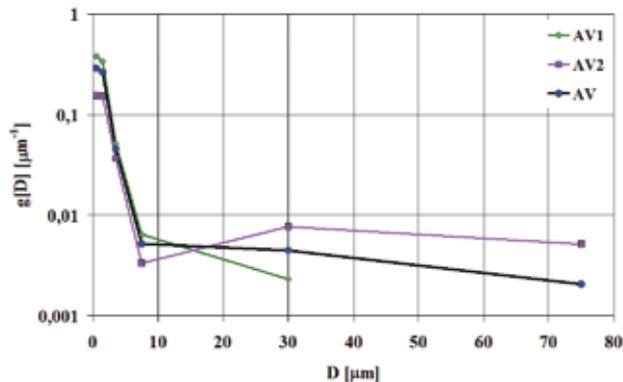


Fig. 11. Probability density of the equivalent diameter of dust particles in the sample taken from the drum brakes: the average values for individual places of analysis (AV1 and AV2) and the average value for the sample as a whole (AV)

Fig. 11 shows the average values of the probability density of the equivalent diameter of dust particles in the sample taken from the drum brakes, i.e. the average values of the probability density for individual places of analysis (AV1 and AV2) and the probability density value averaged for the sample as a whole (AV).

The brake dust examinations carried out at the Automotive Industry Institute (PIMOT) and at the Polish Geological Institute (PGI) showed that the dust samples chiefly consisted of particles containing iron oxidized to different degrees, with barium, silicon, aluminium, calcium, and copper admixtures. Moreover, mineral wool threads, pieces of steel wire, barite particles smaller than 20 μm , numerous brass particles smaller than 10 μm , copper (single grains with their size not exceeding 200 μm), antimonite (of 10-100 μm particle size), and carbonaceous leaves of about 200 μm particle size in the sample were found in the samples. Grains of silver (with their size not exceeding 20 μm), molybdenum (no bigger than 10 μm), magnesium oxide (no bigger than 10 μm , either), and hercynite were also revealed.

The dust particles present in the samples examined had different forms:

- Porous, spherical, and rounded irregularly;
- Fine spherical;
- Fine with sharp edges.

Due to its heavy metal contents, the particulate matter emitted from brake mechanisms is extremely harmful for human health. Figs. 12 and 13 show the share of iron grains in all the particulate matter emitted from the braking systems, in terms of grain cross-sectional area.

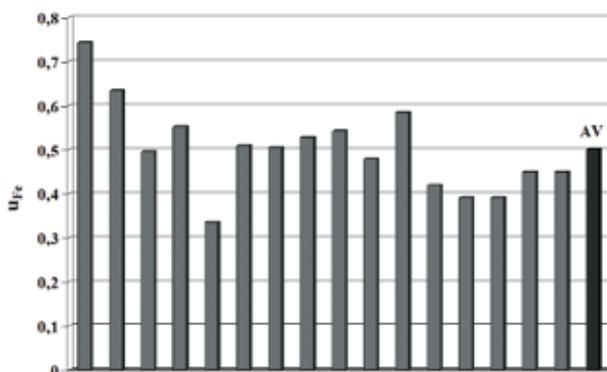


Fig. 12. Share of iron grains in all the particulate matter emitted from the disc brakes (u_{Fe}), in terms of grain cross-sectional area: AV - average value

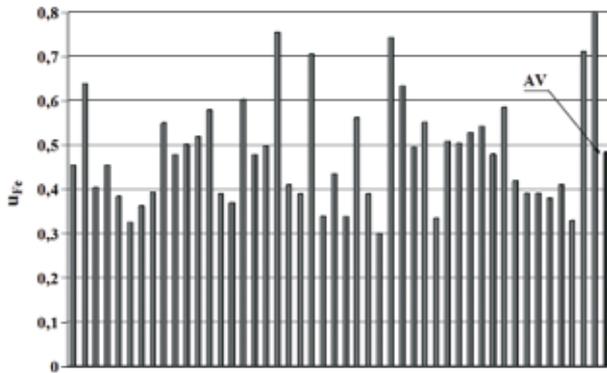


Fig. 13. Share of iron grains in all the particulate matter emitted from the drum brakes (u_{Fe}), in terms of grain cross-sectional area: AV – average value

According to the graphs above, the average share of iron grains in all the particulate matter emitted from the brake mechanisms, in terms of grain cross-sectional area, was about 50%.

3. Recapitulation

Based on the test results presented, the following conclusions may be formulated:

1. In result of the experiments carried out, an original test procedure has been developed for evaluation of the effectiveness of operation of a system to reduce particulate matter emission from brake mechanisms in conditions simulating motor vehicle traffic. Such tests are carried out on a vehicle chassis dynamometer in a driving test with constant vehicle speed, where the vehicle under test is driven by the dynamometer roll and the vehicle brakes are cyclically applied. The test procedure developed has enabled unbiased evaluation of the effectiveness of operation of a system to reduce particulate matter emission from brake mechanisms.
2. The values of the coefficient of effectiveness of the reduction of dust emission from the braking system as determined from rig tests were up to 0.8. The properties of the system developed were confirmed by tests carried out on a vehicle chassis dynamometer, where the coefficient of effectiveness of the reduction of dust emission from the braking system was found to be 0.5 to 0.7.
3. The motor vehicle braking system is a source of emission of particulate matter whose properties are extremely dangerous to human health. Such particles contain heavy metals: in result of the examinations carried out, the average share of iron grains in all the particulate matter emitted from braking systems, in terms of grain cross-sectional area, was found to be about 50%. Moreover, the characteristic dimensions of most

of the particles emitted from braking systems are predominantly smaller than 1 μm ; this has been confirmed by the determined values of the probability densities of the averaged particle diameters.

4. The examinations showed that the average size of most of the dust particles produced during the operation of brake mechanisms was within the range from 0.1 to 0.2 μm .
5. The dust accumulated in the filter chiefly consisted of agglomerates (lumps) of many particles and this explains the fact that the filter arrested smaller particles than could be expected according to filter specifications.
6. Most of the structural components of the friction pair are very finely comminuted and deformed during the braking process, which explains the predominance of particles with a size smaller than 2 μm . Some fine-grained components of the friction material are broken off during the operation of the friction pair and pass into the dust in a practically unchanged state. Metal particles (especially those of the smallest dimensions) may undergo through-oxidation in high temperatures. Other components also undergo changes, especially as the brake disc, judged by colour, reaches a temperature of over 300 °C and the temperature at the contact area in the friction pair is even significantly higher.

The identified dimensional structure of the dust particles produced during the operation of brake mechanisms has confirmed how big a danger can be posed to the human health by the dusts emitted from brake mechanisms of motor vehicles. Such particles are a part of the respirable dust penetrating as deeply as to the alveoli in the lower part of the respiratory tract. Therefore, they may become a source of serious diseases, especially respiratory diseases. This great health hazard caused by the dusts produced during the operation of brake mechanisms provides a good reason for undertaking an initiative to develop systems aimed at a reduction of particulate matter emission from motor vehicle brakes.

Acknowledgements

The publication has been prepared with taking as a basis the results of tests carried out within research and development project No. NR10-0050-10/2010 entitled "Development of systems to reduce dust emission from disc brake and drum brake mechanisms of motor vehicles", financed from the resources of the National Centre for Research and Development.

References

- [1] AGRICOLA G.: *De re metalica*. <http://www.farlang.com/gemstones/agricola-metallica/>.
- [2] ASTM E 2456 – 06. *Standard Terminology Relating to Nanotechnology*.
- [3] CANAGARATNA M.: *Chase studies of particulate emissions from in-use New York City vehicles*. *Aerosol Science and Technology* 2004, 38(6), 555–573.

- [4] CAPES C. E.: *Particle size enlargement*. Elsevier Sci. Publ. Co., Amsterdam 1980.
- [5] CHŁOPEK Z., JAKUBOWSKI A., KIERACIŃSKA A.: *Examination of a laboratory system to reduce dust emission from braking systems of automotive vehicles*. The Archives of Automotive Engineering – Archiwum Motoryzacji 3/2011, 5–17, 103–115.
- [6] CHŁOPEK Z., JAKUBOWSKI A.: *A study of the particulate matter emission from the braking systems of motor vehicles*. Eksploatacja i Niezawodność – Maintenance and Reliability No. 4 (44)/2009, 45–52.
- [7] CHŁOPEK Z., JAKUBOWSKI A.: *Ograniczanie emisji cząstek stałych z układu hamulcowego pojazdu samochodowego (Reduction of particulate matter emission from the braking system of a motor vehicle)*. Archiwum Motoryzacji 1/2010, 3–15 (in Polish).
- [8] CHŁOPEK Z., JAKUBOWSKI A.: *The examination of the reduction of particulate matter emission from motor vehicle braking systems*. Eksploatacja i Niezawodność – Maintenance and Reliability No. 4(48)/2010, 29–36.
- [9] CHŁOPEK Z., ŻEGOTA M.: *The emission of particulate matter PM10 from vehicles*. Eksploatacja i Niezawodność – Maintenance and Reliability No. 1 (21)/2004, 3–13.
- [10] CHŁOPEK Z.: *Modelowanie emisji cząstek stałych PM10 ze źródeł motoryzacyjnych do celów oceny oddziaływania transportu drogowego na środowisko (Modelling of the emission of particulate matter PM10 from automotive sources for the purposes of environmental impact assessment of road transport)*. Report of research project No. N N509 083637 sponsored by the Ministry of Science and Higher Education, Warszawa 2012.
- [11] EN 1540:1998. *Workplace Atmospheres*. Terminology.
- [12] EN 481: 1993. *Workplace atmospheres. Size fraction definitions for measurement of airborne particles*.
- [13] FORSBERG B. et al.: *Comparative health impact assessment of local and regional particulate air pollutants in Scandinavia*. Journal of the Human Environment 34(1), 2005, 11–19.
- [14] HARRISON R. M., JONES A. M., LAWRENCE R. G.: *Major component composition of PM10 and PM2.5 from roadside and urban background sites*. Atmos. Environ 38, 2004, 4531–4538.
- [15] <http://www.commons.wikimedia.org/>
- [16] ISO 4225:1994. *Air quality. General aspects. Vocabulary*.
- [17] ISO 7708:1995. *Air quality. Particle size fraction definitions for health-related sampling*.
- [18] *Lexykon ekoinżynierii (Lexicon of eco-engineering)*. Edited by Gabriel Borowski, Polskie Towarzystwo Inżynierii Ekologicznej (PTIE – Polish Society of Ecological Engineering), Warszawa 2010 (in Polish).
- [19] MACNEE W., DONALDSON K.: *Exacerbations of COPD – environmental mechanism*. Chest 2000, 117, 390–397.
- [20] MAYER A. et al.: *Nanoparticle-emissions of EURO 4 and EURO 5 HDV compared to EURO 3 with and without DPF*. SAE Emissions Measurement and Testing 2007, 335–43.
- [21] PAMPUCH R., HABERKO K., KORDEK M.: *Nauka o procesach ceramicznych (The technology of ceramic processes)*. PWN, Warszawa 1992 (in Polish).
- [22] RADWAG: *Oznaczanie pyłu całkowitego i respirabilnego metodą filtracyjno – wagową na stanowiskach pracy (Determination of total and respirable dust at work stations by a filtration-mass method)*. http://www.radwag.pl/e-sklep/pliki/artykuly/oznaczanie_pylu.pdf (in Polish).
- [23] *Rozporządzenie Ministra Pracy i Polityki Społecznej z dnia 29 listopada 2002 r. w sprawie najwyższych dopuszczalnych stężeń i natężeń czynników szkodliwych dla zdrowia w środowisku pracy (Regulation of the Minister of Labour and Social Policy of 29 November 2002 on the maximum permissible concentrations and intensities of harmful factors in the work environment)*. Dz. U. 2002 No. 217, item 1833 (in Polish).
- [24] SIEMIŃSKI M.: *Środowiskowe zagrożenie zdrowia (Environmental health risk)*. PWN, Warszawa 2001 (in Polish).
- [25] YUH-SHEN WU et al.: *The measurements of ambient particulates (TSP, PM2.5, PM2.5–10), chemical component concentration variation, and mutagenicity study during 1998–2001 in central Taiwan*. Journal of Environmental Science and Health, Part C, Environmental Carcinogenesis and Ecotoxicology Reviews; Volume 20 Issue 1 2002, 45–59.