EXAMINATION OF A LABORATORY SYSTEM TO REDUCE DUST EMISSION FROM BRAKING SYSTEMS OF AUTOMOTIVE VEHICLES

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Summary

Dust is one of the factors that pose most serious danger to human health, especially in densely populated central parts of urban agglomerations. A significant part of dust emissions comes from the motor traffic. Among the dust emission sources related to the vehicle traffic, an important item is the emission of dust from braking systems. A concept to reduce the dust emission from braking systems was developed at PIMOT. A test facility was built, which included a laboratory system to reduce dust emission from braking systems. Preliminary results of the tests carried out showed the proposed solution to be very effective. Empirical tests of the laboratory system were carried out and used for the construction of a mathematical model of the dust emission reduction processes, with the model having been built in accordance with the principle of functional similarity (a behaviouristic model); the results of the tests have been presented in this paper. To identify the model, results of empirical tests carried out on a Krauss test stand were employed. The model examination results presented here provide a possibility of reasonable selection of parameters of the laboratory system. Tests were also carried out to determine the correlation between the coefficient of effectiveness of the reduction of dust emission from the braking system and the independent variables of the model. The examination of the mathematical model unequivocally showed that the effectiveness of the reduction of dust emission most strongly depended on the negative pressure in the pneumatic system. Guidelines for the development work on the proposed concept of a system to reduce dust emission from braking systems have also been presented in this paper.

Keywords: braking systems, dust emission, mathematical modelling, analysis of correlation

1. Introduction

Dust is one of the most environmentally dangerous factors. The harmfulness of dust in the air to human health is commonly known. The first publication that provided information

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about the harmful impact of dust on human health was the Georgius Agricola's work of 1524 entitled "De re metalica" [1]. Since then, the literature covering this subject has become extremely extensive, e.g. [7, 11, 17, 22].

The harmful impact of dust on human health varies depending on chemical and mineralogical composition and physical structure of dust particles [17]. The way of how dust affects living organisms depends very much on dust particle size as well [17, 22]. Dust is categorised as follows, depending on conventional dust particle size [7]:

- TSP (total suspended particles) – a mixture of small solid particles of conventional size below 300 μm, suspended in the air (the dispersed phase of the solid-gas two-phase system);
- PM10 (suspended dust) – of conventional particle size below 10 μm;
- PM2.5 (fine dust) – of conventional particle size below 2.5 μm;
- Nanoparticles – of conventional particle size below 1 μm, which constitute practically invisible dust [8, 13].

Excessive concentration of the particulate matter PM10 in the air is one of the most frequent reasons for remedial actions being taken by the authorities in Poland and other economically developed countries to improve the environmental quality. Since 2009, the PM2.5 concentration has also been limited in the European Union.

The impact of dust on human health may be depicted by the shares of deposition of dust particles arrested in various parts of the human respiratory system vs. the particle diameter, see Fig. 1.

Dust exerts harmful impact not only on human and animal health but also on plants, soil, and water. Dust, together with sulphur dioxide, carbon monoxide, and other chemical compounds, contributes to the generation of the London smog [7, 17]. It also mitigates the

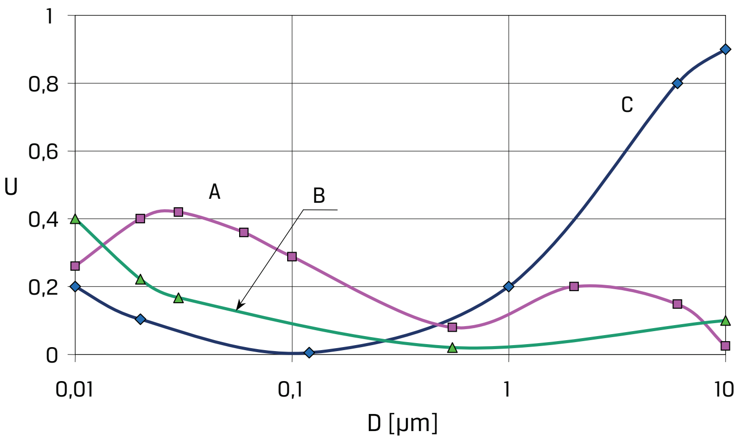

Fig. 1. Distribution of dust particle diameters (shares of deposition, U) arrested in various parts of the human respiratory system (based on [17]): A – lungs; B – trachea and bronchi, C – epipharynx.

greenhouse effect in the atmosphere [17]. Noteworthy is also the fact that dust reduces the visibility and thus impairs the road safety.

The main natural dust emission sources are sedimentary materials; marine, vegetable and animal aerosols; volcano eruptions; and forest fires. The anthropogenic causes for the presence of dust in the air actually include all the production and fuel combustion processes [7, 11].

A special role in the processes of dust emission from anthropogenic sources is played by the road transport because of the masses of automotive vehicles being in use. The dust of automotive origin chiefly comes from the following (see [7, 11]):

- Vehicles;
- Road pavement;
- Solid dirt present on the roads (and stirred up as particulate matter).

In turn, the dust emitted by vehicles comes from the following sources, according to [7, 11]:

- Internal combustion engines (as the particulate matter is present in the exhaust gases) [8, 13, 14];
- Pairs of friction surfaces (chiefly in brakes and clutch);
- Tyres;
- Other vehicle components subject to service wear.

The particulate matter present in the exhaust gases is chiefly emitted by diesel engines; however, a requirement has been provided in the most recent legal regulations on the level of Euro 5 and Euro 6 (or, alternatively, Euro V and Euro VI)[4] that the emission of particulate matter from spark ignition engines should also be taken into account because such engines, especially those with direct injection, may be a significant source of the emission of fine dust (including nanoparticles) [8, 13].

Among the tribological pairs existing in automotive vehicles, the braking system plays a special role because of dust generation. The friction pairs present in the braking system are a significant source of dust emission in connection with the function performed by the brakes, i.e. dissipation of kinetic energy of the vehicle. An average automotive vehicle annually consumes about 0.5 kg of the friction material incorporated in the brakes, according to estimates [3].

The present knowledge of the emission of dust from vehicle braking systems shows that this process has not been sufficiently investigated yet. Results of the research work undertaken at PIMOT (Automotive Industry Institute) on the phenomenon of dust emission from automotive braking systems and on the methods to reduce this emission have been presented in this paper.

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[4] It has become customary to use Arabic numerals for the category of passenger cars and light duty vehicles subject to drive tests on chassis dynamometers (where the "on-road emissions" are determined) and Roman figures for commercial vehicle engines tested on engine test stands (where the "unit emissions" are determined) [20, 21].

2. Examination of a laboratory system to reduce dust emission from a disc brake mechanism

Laboratory systems to reduce dust emission from braking systems were developed at PIMOT [3–5]. Schematic diagrams of the systems to reduce dust emission from disc brake and drum brake mechanisms have been presented in Figs. 2 and 3, respectively.

A detailed description of the method to reduce dust emission from braking systems of automotive vehicles has been provided in patent applications Nos. P 386829 and P 386923.

Preliminary laboratory tests were carried out on a test stand Krauss II RWS75A, model AB 738. This facility has been designed for the testing of the coefficient of friction between friction materials in a disc brake mechanism.

In the system to reduce the dust emission, the dust generated could be transported by air circulation, which might be caused by:

- positive gauge pressure; or
- negative pressure (vacuum).

In result of preliminary tests carried out to identify the problem, the option with negative pressure was chosen. One of the good points of such a solution is a possibility to use the vacuum generated in the engine inlet manifold.

To extract dust from the brake mechanism, products manufactured by Schmalz were used, which included flat oval suction pad NBR45G1/4 cooperating with ejector SEM100SDA and

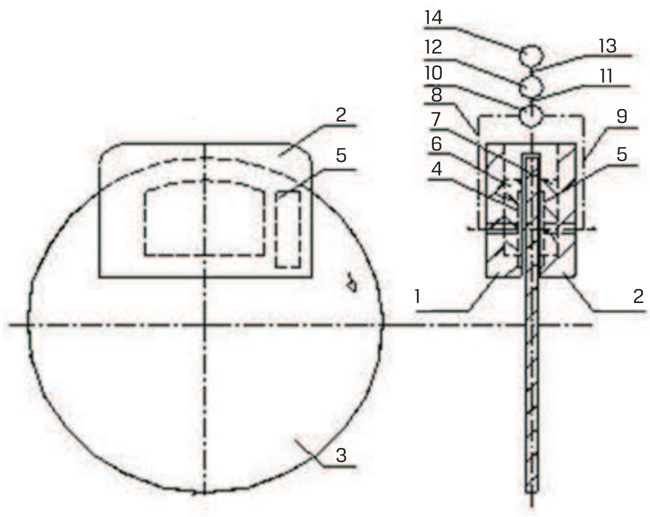

Fig. 2. Schematic diagram of the system to reduce dust emission from a disc brake mechanism. Legend: 1 and 2 – callipers; 3 – brake disc; 4 and 5 – suction holes; 6 and 7 – friction pads; 8, 9, 13 – metal pipes; 10 – pipe tee; 11 – hoses; 12 – filter; 14 – engine inlet manifold.

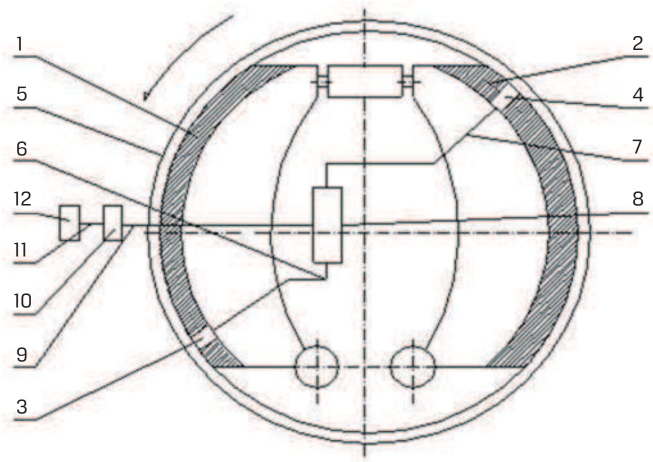

Fig. 3. Schematic diagram of the system to reduce dust emission from a drum brake mechanism. Legend: 1 and 2 – brake shoes; 3 and 4 – suction holes; 5 – brake drum; 6, 7, 11 – metal pipes; 8 – pipe tee; 9 – hoses; 10 – filter; 12 – engine inlet manifold.

filter STF3/4"-IGN for dust of over 3 μm particle size. The rotational speed of the brake disc during tests was 667 min^{-1}.

The preliminary tests were carried out on the following objects:

- Brake disc of a Mercedes car, with 12 mm thickness and 270 mm outside diameter;
- Double-action callipers W 123 of a Mercedes car;
- Friction pads of 55 cm^2 friction area.

In result of the preliminary tests, a decision was taken to situate the suction pad over the friction pads, with a 1.5 mm gap.

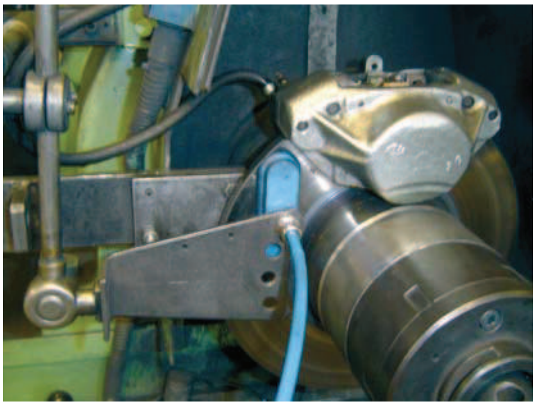

Fig. 4. View of the brake mechanism test setup and the location of the suction pad.

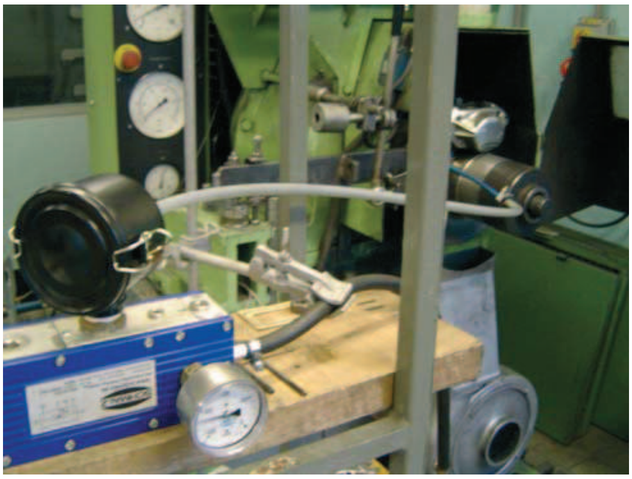

Fig. 5. View of the vacuum system: ejector nozzle with a vacuum gauge and filter connected with the suction pad.

The test facility for the investigation of dust emission from a disc brake mechanism has been presented in photos (Figs. 4 and 5).

The following physical quantities could be controlled, according to the test programme adopted:

- Number of braking cycles;
- Brake disc temperature at which the dust extraction system is switched on (t_a);
- Brake disc temperature at which the dust extraction system is switched off (t_z);
- Negative pressure in the pneumatic dust extraction system (Δp).

Based on the preliminary tests, a decision was taken to apply 100 braking cycles per test.

The empirical tests were used for the construction of a mathematical model of the process of reduction of dust emission from the disc brake mechanism.

To investigate the process of reduction of dust emission from the disc brake mechanism, a model was adopted (1) that was built in accordance with the principle of functional similarity (a behaviouristic model) [6]:

$$k_{PM} = f(t_a, t_z, \Delta p) \quad (1)$$

where k_{PM} is a coefficient of effectiveness of the reduction of dust emission from the braking system of an automotive vehicle, expressed by the following formula:

$$k_{PM} = 1 - \frac{m_k - m_f}{m_k} \quad (2)$$

where: mf – difference between the filter mass before and after the test;
mk – difference between the friction pad mass before and after the test.

The structure of the model was assumed to be in the form of a second-degree function of independent variables:

$$k_{PM} = a_0 + a_{a1} \cdot t_a + a_{a2} \cdot t_a^2 + a_{z1} \cdot t_z + a_{z2} \cdot t_z^2 + a_{p1} \cdot \Delta p + a_{p2} \cdot (\Delta p)^2 \quad (3)$$

To identify the seven parameters of the model, a plan of experiments was adopted, as presented in Table 1 together with the results obtained. The limits for the independent variables were assumed on the grounds of the preliminary problem identification tests.

Table 1. Plan of experiments, together with the results obtained

Δp	ta	tz	kPM
[kPa]	[°C]	[°C]	
32	350	75	0,714
32	175	75	0,663
32	350	125	0,681
32	175	125	0,638
25	350	75	0,609
25	175	75	0,560
25	350	125	0,580
25	175	125	0,537

The test results in graphic form have been presented in Figs. 6 and 7.

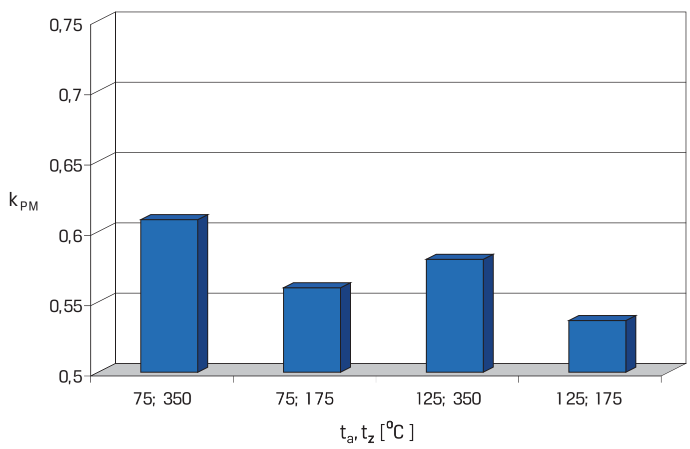

Fig. 6. Test results for a negative pressure of 25 kPa.

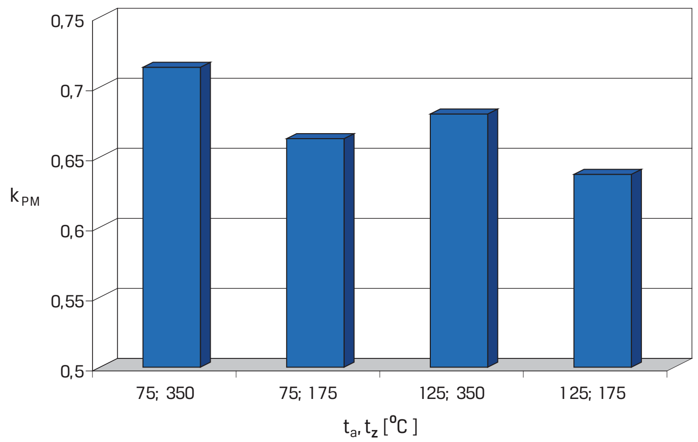

Fig. 7. Test results for a negative pressure of 32 kPa.

The results of the model identification procedure carried out in accordance with the least squares criterion [12] have been given in Table 2.

Table 2. Plan of experiments and the results obtained.

a_0	1,48E–01
a_{a1}	1,55E–02
a_{z1}	3,15E–04
a_{p1}	–6,91E–05
a_{a2}	8,20E–07
a_{z2}	–1,02E–05
a_{p2}	–7,29E–07

The first type of model examination consisted in the evaluation of convergence of combinations of independent variables to the maximum value of the dependent variable. At the examination, the Monte Carlo method was used [2, 15].

Results of testing the convergence of combinations of independent variables at which the dependent variable monotonically increased have been shown in Figs. 8 and 9.

Within the second type of model examination, the correlation between the coefficient of effectiveness of the reduction of dust emission from the braking system and the independent variables was analysed. The examination was carried out for the sets of results of simulation tests of the model.

The analyses were carried out with employing the Pearson linear correlation theory [16]

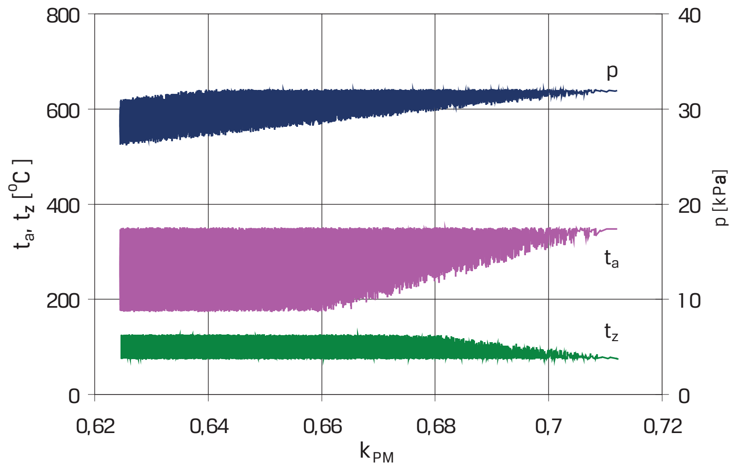

Fig. 8. Convergence of a combination of independent variables at which the value of the dependent variable monotonically increased.

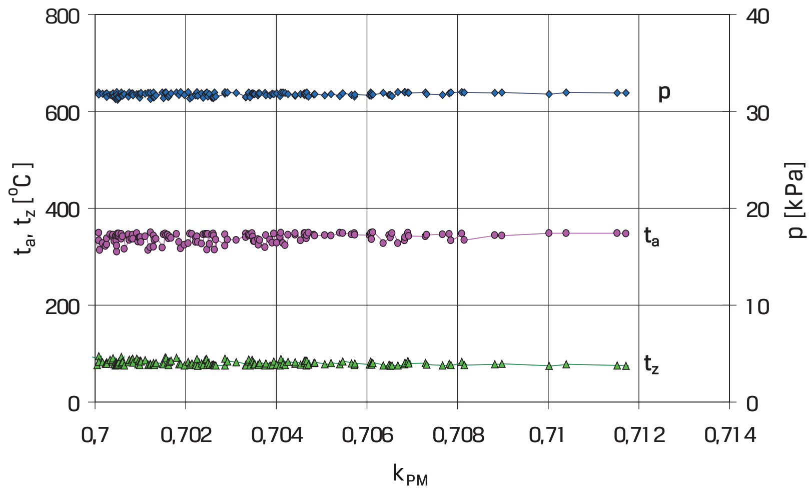

Fig. 9. Convergence of a combination of independent variables at which the value of the dependent variable monotonically increased.

and non-parametric methods [19]: Spearman rank correlation [18], Kendall tau correlation [9], and Kruskal gamma correlation [10].

Results of analysing the results of simulation tests of the model have been shown in Figs. 10 ÷ 12. Each of the figures includes a graph representing the values of the Pearson,

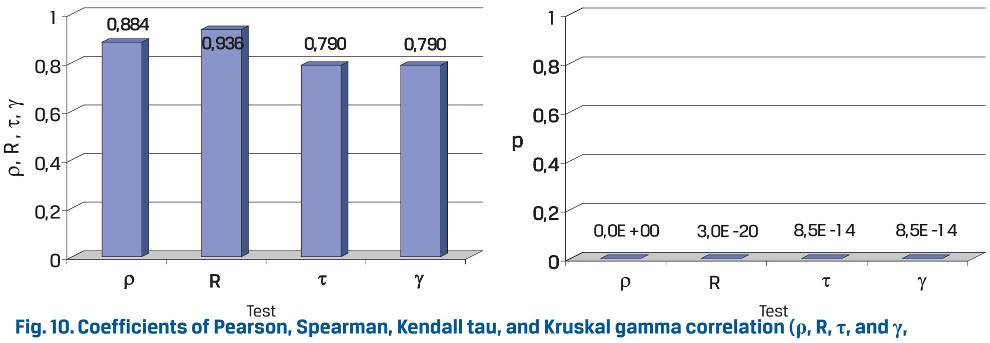

Fig. 10. Coefficients of Pearson, Spearman, Kendall tau, and Kruskal gamma correlation (ρ, R, τ, and γ, respectively) between the negative pressure in the engine inlet system and the coefficient of effectiveness of the reduction of dust emission from the braking system and the probability that the hypothesis of absence of the p correlation will not be rejected.

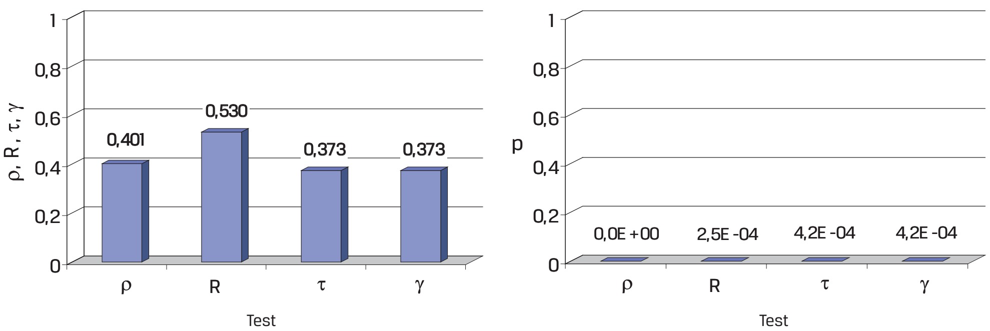

Fig. 11. Coefficients of Pearson, Spearman, Kendall tau, and Kruskal gamma correlation (ρ, R, τ, and γ, respectively) between the brake disc temperature at which the dust extraction system is switched on and the coefficient of effectiveness of the reduction of dust emission from the braking system and the probability that the hypothesis of absence of the p correlation will not be rejected.

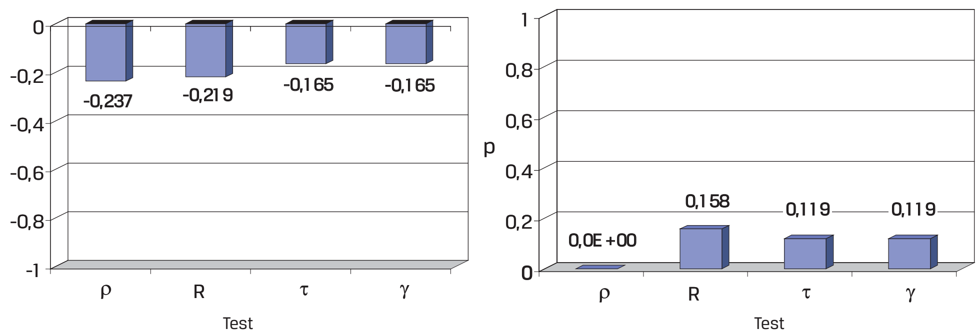

Fig. 12. Coefficients of Pearson, Spearman, Kendall tau, and Kruskal gamma correlation (ρ, R, τ, and γ, respectively) between the brake disc temperature at which the dust extraction system is switched off and the coefficient of effectiveness of the reduction of dust emission from the braking system and the probability that the hypothesis of absence of the p correlation will not be rejected.

Spearman, Kendall tau, and Kruskal gamma correlation coefficients and a graph showing the probability that the hypothesis of absence of correlation for individual correlation types will not be rejected.

Based on the tests carried out, the following in-depth conclusions may be formulated:

- Increase in the absolute value of the negative pressure in the engine inlet system, increase in the brake disc temperature at which the dust extraction system is switched on, and decrease in the brake disc temperature at which the dust extraction system is switched off unequivocally result in a growth in the coefficient of effectiveness of the reduction of dust emission from the braking system.
- The strongest correlation exists between the coefficient of effectiveness of the reduction of dust emission from the braking system and the negative pressure in the engine inlet system; the weakest correlation exists between the coefficient of effectiveness of the reduction of dust emission from the braking system and the brake disc temperature at which the dust extraction system is switched off.

The results of correlational research on the phenomena related to reducing dust emission from the braking system by means of a vacuum system confirm that, in rig test conditions, the performance of the vacuum system developed most strongly depends on the negative pressure used to extract the dust.

The preliminary tests of the laboratory system to reduce dust emission from braking systems of automotive vehicles show that the solution proposed by the authors is an effective method to reduce the environmental hazard posed by dust. The coefficient of effectiveness of the reduction of dust emission from the braking system of an automotive vehicle, as determined at the preliminary tests, even exceeded 70%, which should be considered a very promising result.

3. Plan to develop the concept of a system to reduce dust emission from braking systems

The plan to develop the concept of a system to reduce dust emission from braking systems covers:

- Tests of a pre-prototype system to reduce dust emission from a disc brake mechanism, the system being designed for testing on a Krauss test stand;
- Tests of a pre-prototype system to reduce dust emission from a drum brake mechanism, the system being designed for testing on a Krauss test stand;
- Tests of the reduction of dust emission from a disc brake mechanism and a drum brake mechanism, carried out on a Krauss test stand;
- Tests of the reduction of dust emission from a disc brake mechanism and a drum brake mechanism, carried out on a brake testing stand;
- Tests of vehicle-mounted pre-prototype systems to reduce dust emission from a disc brake mechanism and a drum brake mechanism, carried out on a chassis dynamometer;

- Monitored service tests of vehicle-mounted pre-prototype systems to reduce dust emission from a disc brake mechanism;
- Examination of the composition and particle size of the dust emitted from automotive braking systems;
- Tests to optimise the specifications of systems to reduce dust emission from braking systems;
- Tests to verify the effectiveness of reduction of dust emission from braking systems.

The test programme planned is to result in the working out of guidelines for the construction of prototype systems to reduce dust emission from braking systems.

4. Recapitulation

The emission of dust from anthropogenic sources is one of the most important ecological problems of the present days. Particularly severe dust hazard is encountered in the central parts of urban agglomerations, where the dust emission sources are predominantly related to motor traffic. Among the automotive dust emission sources, particularly important are braking systems, which emit dust of particle size and composition extremely harmful for human health. In this connection, an initiative was undertaken at PIMOT to start research on the emission of dust from braking systems of automotive vehicles and on methods to reduce this emission. Concept designs were prepared and laboratory systems to reduce dust emission from automotive braking systems were made.

Preliminary tests of a laboratory vacuum system designed for a disc brake mechanism made it possible to work out a mathematical model of the process of reduction of dust emission. In the model, the controllable quantities were the negative pressure in the pneumatic dust extraction system and the brake disc temperatures at which the dust extraction system is switched on and off. The examination of the mathematical model unequivocally showed that the effectiveness of the reduction of dust emission most strongly depended on the negative pressure in the pneumatic system. The correlational research on the model showed that the strongest correlation existed between the coefficient of effectiveness of the reduction of dust emission and the negative pressure in the engine inlet system and that the weakest correlation existed between the coefficient of effectiveness of the reduction of dust emission from the braking system and the brake disc temperature at which the dust extraction system was switched off.

The examination of the mathematical model of effectiveness of the reduction of dust emission from braking systems of automotive vehicles has shown that the research method proposed provides a possibility of objective evaluation of the influence of the controlled quantities in the dust extraction system having been built on the system performance. As early as at the stage of problem identification tests, the proposed method to reduce dust emission from braking systems of automotive vehicles was found to be promisingly effective. Therefore, the research work having been undertaken is to be continued and, as a target, the solution developed is to be put into practice. A research programme has been proposed, which is to include the construction of vehicle-mounted systems to reduce dust emission from both disc and drum brake mechanisms. Tests are to be carried out in drive simulation conditions on a chassis dynamometer and in monitored service conditions. In result of the implementation of the research program, guidelines for the construction of prototype systems to reduce dust emission from braking systems will be worked out.

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